Final report of Major Research Project

(From 1/07/2012 – 1/7/2015)

"SYNTHESIS OF DUALBAND BANDPASS FILTER USING PARTICLE SWARM OPTIMIZATION TECHNIQUE FOR WIRELESS APPLICATION"

Submitted to

UNIVERSITY GRANTS COMMISSION,

NEW DELHI

by

Dr. A Thenmozhi

Department of electronics and communication engineering,

Thiagarajar college of engineering,

Madurai – 625 015

UNIVERSITY GRANTS COMMISSION
BAHADUR SHAH ZAFAR MARG
NEW DELHI – 110 002
STATEMENT OF EXPENDITURE IN RESPECT OF MAJOR RESEARCH PROJECT

1. Name of Principal Investigator : Dr. A Thenmozhi
2. Deptt. of University/College : Electronics and Communication Engg. Thiagarajar College of Engineering,Madurai.
3. UGC approval No. and Date : F. No. 41-605/2012 (SR) and 17-07-2012
4. Title of the Research Project : **"Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application"**
5. Effective Date of Starting the Project : 01.07.2012
6. Period of Expenditure : From 01.07.2012 to 31.12.2015
7. Details of Expenditure :

S.No	Item	Amount Approved Rs.	Expenditure incurred Rs.
A.	**Non-Recurring**		
i.	Books & Journals	25000/-	25,054/-
ii.	Equipment (Please Enclose the Quotation)	50,000/-	50,000/-
B.	**Recurring**		
iii.	Contingency	10,000/-	9,000/-
iv.	Field Work/Travel and other Consumables (Give details in the Performa at annexure – VI	20,000/-	26,701/-
v.	Hiring Services	Nil	Nil
vi.	Chemicals, Glassware& Consumable	2,00,000/- **But granted amount – Rs 1,80,000/-**	1,80,000/-
vii.	Overhead	73,800/-	73,800/-
viii.	Any other items (Please specify)	Nil	Nil

8. Staff

Date of Appointment :

S.No	Expenditure Incurred	From	To	Amount Approved (Rs.)	Expenditure Incurred (Rs.)
1.	Honorarium to PI (Retired Teachers) @ Rs. 18,000/-p.m.	Nil	Nil	Nil	Nil
2.	Project fellow: i) NET/GATE qualified-Rs. 16,000/- p.m. for initial 2 years and Rs. 18,000/- p.m. for the third year. ii) Non-GATE/Non-NET- Rs. 14,000/- p.m. for initial 2 years and Rs. 16,000/- p.m. for the third year.	Mr A ChandraPradeepan 13/03/2013 Mr K Karthick 18/09/2013 Ms P Mohana 02.09.2014	30/08/2013 13/09/2014 End of the project	370519/- But Granted Amount – 3,33,467/-	**77,677/-** (5 x 14000/- + 7677/-) **1,68,000/-** (11x 14000/- + 6,067/-+ 7,933/-) **83,533/-** (5 x16000/- +3,533/-) **Total 329,210/-**

1. It is certified that the appointment(s) have been made in accordance with the terms and conditions laid down by the Commission.
2. It as a result of check or audit objective, some irregularly is noticed, later date, action will be taken to refund, adjust or regularize the objecte amounts.
3. Payment @ revised rates shall be made with arrears on the availability of additional funds.
4. It is certified that the grant of **Rs. 6,89,267/-** (Rupees Six Lakh Eighty Nine Thousand Two Hundred and sixty seven only) received from the University Grants Commission under the scheme of support for Major Research Project entitled **Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application** vide UGC letter No. F. No. 41-605/2012 (SR) dated 17-07-2012 a sum of **Rs. 6,93,713/-** has been fully utilized for the purpose for which it was sanctioned and in accordance with the terms and conditions laid down by the University Grants Commission.

PRINCIPAL INVESTIGATOR

REGISTRAR/PRINCIPAL

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

Annexure – IV

UNIVERSITY GRANTS COMMISSION

BAHADUR SHAH ZAFAR MARG

NEW DELHI – 110 002

STATEMENT OF EXPENDITURE INCURRED ON FIELD WORK

Name of the Principal Investigator : Dr. A Thenmozhi

Name of the Place Visited	Duration of the Visit		Mode of Journey	Expenditure Incurred (Rs.)
	From	To		
NIT,Trichy	Madurai	Trichy	Bus	2,420/-
UGC, New Delhi	Madurai	New Delhi	Flight	24,281/-
			Total	26,701/-

Certified that the above expenditure is in accordance with the UGC norms for Major Research Projects.

SIGNATURE OF
PRINCIPAL INVESTIGATOR

REGISTRAR/PRINCIPAL

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

Annexure - V

UNIVERSITY GRANTS COMMISSION

BAHADUR SHAH ZAFAR MARG

NEW DELHI – 110 002

Utilization Certificate

Certified that the grant of **Rs.6,89,267/-** (Rupees Six Lakh eighty nine thousand two hundred and sixty seven only) received from the University Grants Commission under the scheme of support for Major Research Project entitled "**Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application**" vide UGC letter **F. No. 41-605/2012 (SR) and 17-07-2012** of **Rs 6,93,713/-**(Rupees Six Lakh ninety three thousand seven hundred and thirteen only) has been fully utilized for the purpose for which it was sanctioned and in accordance with the terms and conditions laid down by the University Grants Commission.

SIGNATURE OF THE PRINCIPAL INVESTIGATOR

REGISTRAR/PRINCIPAL
(Seal)
PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

THIAGARAJAR COLLEGE OF ENGINEERING MADURAI 625 015

M. Vijayan

STATUTORY AUDITOR

(Seal)

M. VIJAYAN, B.Com., F.C.A.,
Chartered Accountant
Membership No : 200/26972
9,Venkataraman Road, Kamala 2nd St.,
Chinna Chokkikulam, Madurai-625 002

M. VIJAYAN, B.Com., F.C.A. Madurai Membership No: 26972 CHARTERED ACCOUNTANT

ANNEXURE - VI

ज्ञान-विज्ञान विमुक्तये

PROFORMA FOR SUPPLYING THE INFORMATION IN RESPECT OF THE STAFF APPOINTED UNDER THE SCHEME OF MAJOR RESEARCH PROJECT

UGC FILE NO. F. No. 41-605/2012 (SR) **YEAR OF COMMENCEMENT** 0 1 | 0 7 | 2 0 1 2

TITLE OF THE PROJECT: "Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application"

1.	Name of the Principal Investigator	Dr. A Thenmozhi
2.	Name of the University/College	Thiagarajar College of Engineering, Madurai - 625 015
3.	Name of the Research Personnel appointed	1. Ms. P.Mohana 2. Mr K Karthick 3. Mr A Chandra Pradeepan
4.	Academic Qualification	**S. No** / **Qualifications** / **Year** / **Marks (CGPA)** 1. / M.E. (ECE) / 2014 / 8.1 2. / B.E (ECE) / 2012 / 69.5 3. / B.E (ECE) / 2012 / 7.57
5.	Date of Joining	1. 02-09-2014 --- Ms P Mohana 2. 18.09.2013 --- Mr K Karthick 3. 13.03.2013 --- Mr A Chandra Pradeepan
6.	Date of Birth of Research Personnel	1. 05-06-1990 --- Ms P Mohana 2. 05.12.1985 --- Mr K Karthick 3. 16.07.1990 --- Mr A Chandra Pradeepan
7.	Amount of HRA, if drawn	Nil
8.	Number of Candidate applied for the post	3

CERTIFICATE

This is to certify that all the rules and regulations of UGC Major Research Project outlined in the guidelineshave been followed. Any lapse on the part of the University will liable to terminate of said UGC project.

Principal Investigator	Head of the Deptt. 9/6/16	Registrar/Principal

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

MADURAI 625 015
THIAGARAJAR COLLEGE OF ENGINEERING

Annexure -VIII

UNIVERSITY GRANTS COMMISSION
BAHADUR SHAH ZAFAR MARG
NEW DELHI – 110 002.

Final Report of the work done on the Major Research Project.
(Report to be submitted within 6 weeks after completion of each year)

1.	Project report No. 1st/2nd/3rd/Final	Final Report
2	UGC Reference No	F. No. 41-605/2012 (SR) and Dated 17-07-2012
3	Period of report	From July 2012 to December 2015
4	Title of research project	Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application
5	a. Name of the Principal Investigator	Dr. A Thenmozhi
	b. Dept. and University/College where work has progressed	Electronics and Communication Engineering, Thiagarajar College of Engineering, Madurai-15
6	Effective date of starting of the project	01.07.2012
7	Grant approved and expenditure incurred during the period of the report:	
	a. Total amount approved	Rs. 7,49,319/-
	b. Amount Granted for 1st Instalment	Rs. 5,27,800/-
	c. Amount Granted for 2nd Instalment	Rs. 1,61,467/-
	d. Total expenditure	Rs. 6, 93, 713/-
	e. Report of the work done	Enclosed
	i. Brief objective of the project	Attached
	ii. Work done so far and results achieved and publications, if any, resulting from the work (Give details of the papers and names of the journals in which it has been published or accepted for publication)	Attached
	iii. Has the progress been according to original plan of work and towards achieving the objective. if not, state reasons	Yes
	iv. Please indicate the difficulties, if any, experienced in implementing the project	Nil
	v. If project has not been completed, please indicate the approximate time by	Completed

	which it is likely to be completed. A summary of the work done for the period(Annual basis) may please be sent to the Commission on separate sheet	
	vi. If the project has been completed, please enclose a summary of the findings of the study. Two bound copies of the final report of work done may also be sent to the Commission	Enclosed
	vii. Any other information which would help in evaluation of work done on the project. At the completion of the project the first report should indicate the output, such as(a) Manpower trained (b) Ph. D awarded (c) Publication of results (d) other impact, if any	• 1 Master Degree Projects Completed; • Expertise has been shared with rural students through lectures in seminars and symposiums

SIGNATURE OF THE

PRINCIPAL INVESTIGATOR

REGISTRAR/PRINCIPAL

THIAGARAJAR COLLEGE OF ENGINEERING MADURAI 625 015

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

,ANDATE FORM FOR THE INSTITUTIONS REGISTERED OR MAPPED UNDER PFMS

ELECTRONIC CLEARING SERVICE (CREDIT CLEARING)/REAL TIME GROSS SETTLEMENT (RTGS) FACILITY FOR RECEIVING PAYMENTS

A. DETAIL OF ACCOUNT HOLDER	
ACCOUNT HOLDER (REGISTRAR/DIRECTOR/PRINCIPAL/ETC.)	THE PRINCIPAL, THIAGARAJAR COLLEGE OF ENGG
COMPLETE CONTACT ADDRESS	THIAGARAJAR COLLEGE OF ENGINEERING, THIRUPARANKUNDAM MADURAI - 625015
TELEPHONE NUMBER/FAX/EMAIL	0452-2482430 / 0452-2483427/ principal@tce.edu
B. BANK ACCOUNT DETAILS	
BANK NAME	ICICI BANK LTD
BRANCH NAME WITH COMPLETE ADDRESS, TELEPHONE NUMBER AND EMAIL	THIAGARAJAR COLLEGE OF ENGG BRANCH; THIRUPARANKUNDAM MADURAI – 625015; PHONE: 0452-2482810 Mail ID: selvakrishnan.sadagoparamanujam@icicibank.com
WHETHER THE BANK IS COMPUTERIZED?	YES
WHETHER THE BRANCH IS RTGS ENABLED? IF YES, THEN WHAT IS BRANCH'S IFSC CODE	YES, ICIC0000563
IS THE BRANCH ALSO NEFT ENABLED?	YES
TYPE OF BANK ACCOUNT(SB/CURRENT/CASH/CREDIT)	SB
COMPLETE BANK ACCOUNT NUMBER(LATEST)	ACCOUNT NAME : TCE-DRDL PROJECT A/C ACCOUNT NO : 601301905856
MICR CODE OF BANK	625229014
UNIQUE CODE OF PFMS	TCE

I hereby declare that the particulars given below are correct and complete. If the transaction is delayed or not effected at all for reasons of incomplete or incorrect information I would not hold the user institution responsible. I have read the option invitation letter and agree to discharge responsibility expected of me as a participant under the scheme.

The above institution, account number and bank details are registered / mapped under PUBLIC FINANCE Management SYSTEM (PFMS).

(-----------------------------)
Signature of Customer
Principal
THIAGARAJAR COLLEGE OF ENGINE...
MADURAI-15.

Date:

Certified that the particulars furnished above are correct as per our records.

For ICICI Bank Limited

Bank's Stamp ICICI BANK LTD. TCE Branch (0563)

(-----------------------------)
105803 Banker's Signature
Authorised Signatory

Date: 20.02.2017

1. Please attach a photocopy of cheque along with the verification obtained from the bank
2. In case your bank branch is presently not "RTGS Enabled", then upon its up gradation to "RTGS Enabled" branch, please submit the information again in the above proforma to the department at earliest.

Attested

ICICI Bank

Application for National Electronic Fund Transfer (NEFT)/
नेशनल इलेक्ट्रॉनिक फंड ट्रांसफर (एन ई एफ टी) के लिए आवेदन

To,/ प्रति,
The Branch Manager/ शाखा प्रबंधक
TCE Branch/ शाखा

Date/ दिनांक 03/12/2018

PAN No./ पैन नं.
*To be provided by ICICI Bank Customer/ * केवल आई सी आई सी आई बैंक के ग्राहक भरें

Dear Sir/प्रिय महोदय,
Please remit through NEFT a sum of ₹ 5321/- (Rupees in words) Five Thousand Three Hundred Twenty one only
as per details given below:
कृपया निम्नांकित विवरण अनुसार एन ई एफ टी के माध्यम से ₹ (रुपये शब्दों में) मात्र प्रेषित (रेमिट) करें.
☐ Cash/ नकद ☑ Cheque/ चेक ☐ Debit my/our account/ मेरा/हमारा खाता डेबिट करें
*In case of cash, please fill in the pay-in-slip / *नकदी की दशा में कृपया जमा पर्ची (पे-इन-स्लिप) भरें
*To be filled by the Applicant in CAPITAL LETTERS / आवेदक द्वारा बड़े रूप अक्षरों में लिखा जाए

DETAILS OF APPLICANT (REMITTER)/ आवेदक (प्रेषक) का विवरण

Account Number/ खाता संख्या:	601301190585 6
Cheque Number/ चेक संख्या:	002918
Cheque Date/ चेक दिनांक:	03/12/2018
Remitter's Name/ आवेदक/प्रेषक का नाम:	TCE DRDL PROJECT
Address/ पता:	TCE
	TPK MADURAI - 15
Mobile/ Other Number/ मोबाइल/अन्य नंबर:	

DETAILS OF BENEFICIARY/ हिताधिकारी का विवरण

Beneficiary's Name/ हिताधिकारी का नाम:	SECRETARY UGC NEWDELHI
Account Number/ खाता संख्या:	86271010002122
Bank Name/ बैंक का नाम:	CANARA BANK
IFSC Code (11-digit) / आई एफ एस सी कोड (11-अंक)	CNRB0008627
Branch Address/ शाखा का पता:	UGC OFFICE NEW DELHI
Mention Account Number Again/ पुनः खाता संख्या लिखें:	86271010002122
Remarks (if any)/ टिप्पणी (यदि हो):	

Terms and Conditions/ नियम और शर्तें

- This transfer is valid for a single transaction./ यह ट्रांसफर एकल व्यवहार (ट्रांजैक्शन) के लिए ही मान्य है.
- The fund transfer will be governed by the Terms and Conditions given on our website www.icicibank.com./ फंड ट्रांसफर हमारी वेबसाइट www.icicibank.com पर दिए गए नियमों व शर्तों द्वारा शासित होगा.
- I / We authorise ICICI Bank to recover charges as may be applicable by debiting my account as mentioned above./ मैं/ हम आई सी आई सी आई बैंक को अधिकृत करते हैं कि वह लागू शुल्कों को मेरे उपरोक्त खाते में डेबिट करके वसूल करे.
- I / We understand that as per the RBI circular dated October 14, 2010, transfer of funds through electronic mode will be executed only on the basis of the account number of the beneficiary provided while initiating the transaction; name will not be considered as a criteria for providing credit./ मैं/हम जानते हैं कि आर बी आई परिपत्र दिनांक 14 अक्टूबर, 2010 के अनुसार, इलेक्ट्रॉनिक विधि के माध्यम से फंड्स का ट्रांसफर ट्रांजैक्शन करते समय दिए गए केवल हिताधिकारी की खाता संख्या के आधार पर ही होगा, और क्रेडिट देने के लिए नाम के मापदंड पर विचार नहीं किया जाएगा.
- I understand that this facility is available only at select locations and banks covered under Electronic Funds Transfer facility offered by RBI. मुझे पता है कि यह सुविधा केवल चुनिंदा स्थानों और बैंकों में ही उपलब्ध है, जो आर बी आई द्वारा दी गई इलेक्ट्रॉनिक फंड ट्रांसफर सुविधा के अंतर्गत शामिल हैं.
- Transfer of an amount up to ₹ 49,999 in cash permissible using this facility./यह सुविधा प्रयोग करके रु.49,999 तक की राशि नकद ट्रांसफर कर सकते हैं.
- Photo ID proof to be given by non customer for cash payment above ₹ 5,000 / ₹ 5,000 से अधिक के भुगतान के लिए गैर-ग्राहकों को फोटो पहचान-पत्र देना होगा.

Customer Signature (s) ग्राहक के हस्ताक्षर

Signature / हस्ताक्षर

Signature / हस्ताक्षर

Signature / हस्ताक्षर

Name/नाम

Name/नाम

PA TO PRINCIPAL / MANAGER

*(Primary Applicant /प्राथमिक आवेदक) *(Joint Applicant 1/ संयुक्त आवेदक 1) *(Joint Applicant 2 / संयुक्त आवेदक 2)

Customer Acknowledgment/ ग्राहक की रसीद

Date/ दिनांक :

We acknowledge receipt of NEFT instruction(s). Reference no./
हम एन ई एफ टी निदेश की प्राप्ति को स्वीकार करते हैं. संदर्भ क्र.

Branch/ शाखा : Name and Signature of Bank Official / बैंक अधिकारी का नाम व हस्ताक्षर

ICICI BANK LTD.
TCE Branch, Madurai (0563)

ICICI BANK LTD
TCE Branch Madurai (0563)

Attested

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

5/19

Introduction

A microwave filter is being used to provide band selectivity in mobile communication and satellite communication, RADAR and remote sensing systems operating at microwave frequencies. Basically, for filters with high-frequency selectivity, the guard band between channels can be made very small. Although a tremendous amount of research and development had been devoted to microwave filter theory and technology, as specifications for the required filters become more and more stringent, the need of newer approaches for design and fabrication is still increasing. Characterization of filter structures has two major components namely analysis and synthesis. Analysis is the process of obtaining electrical parameters of the filters from the given physical parameters whereas synthesis is the process of obtaining the physical parameters of filter structures for the specified electrical parameters.

Since early part of the century, the classical Butterworth and Chebyshev approximations were used for the filter network synthesis. Distributed filter structure designs are being carried out by either image parameter techniques or insertion loss techniques using approximations based on classical Butterworth and Chebyshev functions. However, the tuning of these microwave filters became a difficult task, especially when the transfer function had the maximum allowable number of transmission zeros and poles. An alternative approach is to iteratively adjust a set of filter element values until the zeros, poles, and the scale factor of the characteristic function of the microwave filter match with the required values resulting in the desired response. The main aim of this project is to reduce the optimization time to reach the required specification of the filter response.

Literature survey Report

Filter is a component that provides the front end band selectivity in wireless and satellite communications, radar, electronic warfare, and remote sensing systems operating at microwave frequencies. In general, the electrical performance of filters is described in terms of insertion loss, return loss, bandwidth and group-delay. Filters are required to have a small insertion loss and a large return loss for good impedance matching with interconnecting components and high-frequency selectivity to prevent interference. Hence, the guard band between channels can be made very small for filters with high frequency selectivity. Further, smaller group delay and smaller amplitude variation of the filter response in the pass band are required for minimum signal degradation. Although a tremendous amount of research and development has been devoted to microwave filter theory and technology, as the specifications for the required filters become more and more stringent, the need for further development of new approaches in respect of design and fabrication techniques are still increasing.

- **OPTIMIZATION FOR FILTER DESIGN**

In recent years the design of microwave filters involved the application of some kind of synthesis to meet the desired electrical specifications. Microwave filter synthesis is divided into two optimization processes namely; parametric optimization for component values and topological optimization for filter structures. In general, the topological optimization is more difficult than the parametric one, since there are no simple rules to describe microwave filter topology and there is a huge set of possible topologies even in the case of very few components (Shibata et al 2003). However, in this case one can explore the possibilities unconventional topologies that will result in the desired response. Many optimization methods have been demonstrated in order to synthesis and tune the microwave filters.

Optimization techniques such as the gradient-based method (Bandler et al 1994), space mapping (Bandler et al 2002, Bandler et al 2004), and neural networks (Rayas-Sanchez 2004) are available for the design of microwave circuits. Hsu and Huang (Hsu and Huang 2005) proposed a simulated annealing algorithm to design dual-wideband microstrip line filters for WLAN applications. This approach worked on the electrical parameters based on a given circuit topology. A great deal of effort has been made on searching for the design parameters based on a given circuit topology. Only a few attempts thus far have been made at developing an algorithm capable of searching for the circuit topology, as well as the electrical parameters simultaneously. It has been reported in the literature that Evolutionary Algorithms have the capability to optimize both the topology and the parameters of the filter. These algorithms work with the design goals, a set of available models and the constraints. Genetic algorithms (GAs), first introduced by Holland in 1975, have been widely used in science and engineering problems (Goldberg 1989, Gen and Cheng 2000) has proved to be useful for solving complex electromagnetic problems (Ruhmat-Samii and Michielssen 1999, Choo and Ling 2003, Chakravarty et al 2002, Wener et al 2000, Peik and Chow 1997, Nishino and Itoh 2002, Nishino and Itoh 2003).

For microwave filters synthesis, Peik and Chow (1997) focused on searching for the optimal electrical parameters based on a given circuit topology. Nishino and Itoh (2002) proposed a scheme to describe the physical parameters and topology of the circuit and integrated this representation scheme with conventional GAs (Nishino and Itoh 2003). Then these methods are used to explore an efficient computer-aided tool, to synthesize dual-band band pass filters including the circuit topology, as well as the corresponding electrical parameters. Since the conventional optimization algorithms are used for model parameter extraction, for this type of multi-parameter optimization, global optimization algorithms such as genetic algorithm have been attempted. However the genetic operators, such as selection, crossover, and mutation are relatively complex (Zhen and Lihui 2003).

The PSO has been recently introduced to electromagnetic community for optimization process (Robinson and Rahmat-Samii 2004). PSO is a robust stochastic evolutionary technique based on the movement and intelligence of swarms which has been shown to be effective in optimizing complicated multidimensional problems. PSO has been applied for modeling, design and optimization of RF passive devices such as inductors, filters and antennas (Mandal and Arijit-De 2005). PSO method was used for the design of microstrip coupled transmission line filter for Ultra Wide Band systems by Zhang and Feng (2006).

PSO is akin to Genetic Algorithm and simulated annealing in as much as it is a stochastic method performing a global search in the parameter space without getting trapped in to local minima. Motekovits et al (2004) have applied PSO for the design of symmetric microstrip band pass filter. It has the inherent simplicity of GA while converges much faster than conventional evolutionary algorithms. Mahanfar presented a simple and universal design procedure for planar microwave band pass filter and inferred that PSO method is fast, robust and well suited for fast paced engineering design environment. Wang et al have proposed a novel design approach for planar microwave filters with irregular shapes, which lead to more freedom and possible optimal designs. The finite element method and particle swarm optimization tools are combined together for the search of optimal filter structure leading to miniaturization (Wang et al 2005).

The ever-increasing demand of wireless communication applications necessitates RF transceivers operating at multiple frequency bands such that the users can access various services with a single multimode handset. To reduce the volume and weight of communication circuits and equipment, many dual-band and multi-band components, including antennas (Kuo and Wong 2003), amplifiers (Hashemi and Hajimiri 2002) and filters (Miyake et al 1997, Tsai and Hsue 2004, Chang et al 2004, Uchida et al 2004) have been developed. The dual-band band pass filter consists of two single-band band pass filters operating at the upper band and the lower band which can be simply connected to achieve the desired dual-band band pass filter, although tuning between the two single band filters is very difficult and size of the filter is also increased.

To realize the dual band filter, Wada and Hashimoto (2000) have attached a lumped capacitor to the center of an open-circuited uniform impedance resonator (UIR). The capacitor will lower the even mode resonance and will not affect the odd resonances. Therefore, the second frequency of the structure will be limited to be lower than twice the first one.

Dual-band filters have been proposed by Yamashita, using Stepped Impedance resonator (SIR). This SIR can control second passband by adjusting its impedance ratio and the electric lengths (Makimoto and Yamashita 1980). By properly selecting the relevant impedance or strip width ratio, the dual-band filters can be created using this SIRs (Chang et al 2004). For improving insertion losses in both dual pass bands, the external feed lines require an additional impedance transformer to make perfect impedance matching (Lee 2004). Due to this the size and complexity of the design have become the key issues.

If a SIR is employed, both the fundamental and the second resonances can be easily adjusted over a wide frequency range by simply changing its structural parameters (Kuo and Shih 2003). As a result, the second resonance can be either higher or lower than twice the fundamental one. Chang et al have used SIRs to successfully design dual-band filters in comb and hairpin structures. Unfortunately, the filter order and description of design methods are limited. Thus far, it is still a real challenge to circuit designers in designing a single filter with two pass bands which are simultaneously synthesized. Kuo and Cheng (2004) have described the planar filters with a dual-pass band response with the help of quasi-elliptic function. In this, four hairpin resonators with two different geometric dimensions are designed to establish appropriate couplings in the cross-coupled structure.

During 2005, Sun S and Zhu L have explained the dual-band filter without any external impedance transformer (Sun and Zhu 2005) and its overall size was further minimized (Sun and Zhu 2005). But the second passband of the above dual-band filters has higher insertion loss about 3 dB or more than 3 dB. Alternatively, Chen and Hsu (2006) have used folded open-loop ring resonators (OLRR) to create a virtually lossless dual-band microstrip filter. The filter is comprised of two uniform microstrip lines and two pairs of OLLRs. The OLRRs are placed between two microstrip lines and each has a perimeter about a half-wavelength. Half-wavelength OLRRs is applied to design planar band pass and band stop filters. Each of the fold half-wavelength ring resonators has the maximum electric field density near the open ends of the line, and the maximum magnetic field density around the center valley of the line at resonance. This dual-band filter using coupling mechanism which has advantages of low insertion loss, wide tunable range of either pass band, transmission zeros, easy to design, and without external impedance-matching block.

Dual band pass filters are realized in monolithic (Miyake et al 1997) and planar forms (Wada and Hashimoto 2000, Tsai and Hsue 2004, Kuo and Cheng 2004). The dual band pass filter realization consists of two integrated circuits, and each of them is implemented individually for one frequency band. This is a viable alternative using a double diplexing scheme consisting of two distinct filters which are diplexed at each end to achieve the desired two-port dual-band characteristics. In this way, extra impedance-matching networks have to be designed for the two-in and two-out structure (Miyake et al 1997). Tsai and Hsue have described a dual-band bandpass filter by a cascade connection of a band pass and a band stop filter (Tsai and Hsue 2004). During 2006, Chen and Hsu have explained a resonator which is embedded into another one to obtain two pass bands.

The synthesis of a microwave filter starts with the selection of a transfer function that fulfills the electrical specifications. For single-band filtering characteristics, quasi-elliptic polynomial functions given by explicit formulas are widely employed

(Cameron 1999). The synthesis of microwave filters presenting two pass bands has been faced in the past, using frequency-variable transformations based on the Zoltarev function (Levy 1970, Bell 2001); this approach did not allow to control the attenuation of the stop band between two pass bands. Moreover, the trend today is towards solutions using planar filters such as coupled lines or topologies with transmission zeros (Hong and Lancaster 1996, Quendo et al 2004). They are very attractive because of the reduced bulk and low production cost. These considerations led to use dual-behavior resonators (DBRs) because they are planar and induce transmission zeros (Quendo et al 2003, Quendo et al 2004).

The DBR topology is one among the alternative solutions to reduce above said constraints. It consists of a two different stop band structures in parallel connection. Each of them brings its own transmission zero on either side of the pole (Quendo et al 2003, Quendo 2004) to obtain the dual pass band. A very easy way to design such a resonator is to associate two different open-ended stubs in parallel. This solution is very interesting in a limited band because of low insertion loss, good flatness, and high rejection level, but also of size and cost. Unfortunately this method generates spurious harmonics which appears on either side of the band pass response, that have to be carefully eliminated. Spurious resonance in the low-frequency band can be suppressed by employing short-circuited stubs as stop band structure (Quendo et al 2004). But, this solution implies the use of via holes and, thus, relies on a more complex technological process. Manchec et al have proposed open-ended stubs for utilizing the stop band structures in the DBRs associated with capacitive inverters to keep a via-less solution (Manchec et al 2006). The resulting structure is called capacitive-coupled dual-behavior resonator (CCDBR) filter and dedicated to the elimination of spurious resonances at low frequency. However, getting the desired value of the capacitances from a classical planar technology is very difficult. This is solved by moving the coupling to the resonators, which leads to physically acceptable solutions. Conversely, the secondary effects of the resonators have to be neglected. Another way to eliminate the spurious responses a robust optimization technique is required to place the zeros on either side of the poles.

Peik and Chow (1997) have developed an algorithm on searching for the optimal electrical parameters based on a given circuit topology to reduce spurious responses. Many filters with several pass bands and stop bands were found by Nishino and Itoh (2002). Nevertheless, the representation scheme merely modeled by the transmission-line segments with equal width and open-circuited shunt stubs (Nishino and Itoh 2002); it is difficult to realize dual-band band pass filters with sharp cutoff in the pass bands, as well as good rejections in the stop bands. The synthesis of these kinds of filters could be analytically approached with a general pole-zero placing technique (Amari 2000, Mokhtaari et al 2006); however, since this technique is based on numerical optimization, the convergence is not always guaranteed and its effectiveness may be questionable especially in the case of high-selectivity requirements.

Uchida et al (2004) have developed a band pass filter with smaller insertion loss through the formation of two closely spaced rejection bands, using a novel frequency-transformation technique. This technique has been borrowed and extended by Guan et al (2005), and is proposed to facilitate the design of dual-band BPFs. This theory has commenced a conventional prototype low pass filter (LPF) and a frequency transformation, which converts the prototype LPF into a band pass filter (BPF). After a second frequency transformation is carried out, the BPF is converted into a dual-band BPF. The dual-band BPF owns a different configuration compared with those of conventional BPFs. To simplify the realization of the obtained dual-band BPF using distributed transmission lines or waveguides, admittance inverters are introduced successively to evolve the filter into new topologies. The final circuitry of the dual-band filter consists of only series *LC* resonators and admittance inverters, and hence can be easily realized by using distributed transmission lines and conventional design techniques. The Design of dual-band band pass filter sensitivity depends upon the location of transmission zeros at both ends of the bands. Hence an efficient optimization procedure for generating dual band characteristics which guarantees that for critical specifications in the stopband and the passband of an optimal response is obtained (Lunot et al 2007).

- **ISSUES WITH DUAL BAND FILTER**

Basically, a dual-band filter is a combination of two different single-band filters (Miyake et al 1997) but suffers from high insertion loss, poor return loss and increased size. The PSO based optimization of filters, considered a circuit parameter namely insertion loss as an objective and hence configured a combination of a class of filter elements (resonators) to meet the desired response. However, in a filter there are other circuit parameters such as return loss can influence the response. Being conflicting in their behaviors there is an essential requirement for considering both insertion loss and return loss simultaneously for the design of optimal band pass filter.

Objectives of the project

- To develop a novel synthesis procedure for the design of microwave band pass filter with stringent requirements such as small size, high performance means sharp cutoff, low insertion loss in the pass bands, and better out-of-band rejection.
- To design a dual-band filter with transmission zeros of the required bands.

Algorithm development Report

- **Particle Swarm Optimization (PSO)**

The particle swarm optimization (PSO) technique is a relatively new technique for microwave community. It has received a huge attention and popularity due to its algorithmic simplicity and effectiveness for solving complicated microwave problems. The Particle Swarm Optimization (PSO) technique has been developed by Eberhart and Kennedy in 1995 and it is a simple evolutionary algorithm which differs from other evolutionary computation techniques which is motivated from the simulation of social behavior (Kennedy and Eberhart 1995).

Particle swarm (PS) procedure is gaining popularity due to its inherent simplicity and faster convergence (Kennedy and Eberhart 2001, Clerc and Kennedy 2002) than other conventional evolutionary algorithms like Genetic algorithm. PSO is the extension of genetic algorithms (GA), which performs a global search in the parameter space without getting trapped in to local minima. PSO is an effective population based self adaptive search optimization method, which has been successfully applied in the electromagnetic field for optimization. Compared to GA (Yeo and Lu 1999), the advantages of PSO are that it is easy to implement and there are few parameters to adjust (Yeo and Lu 199

❖ Methodology:

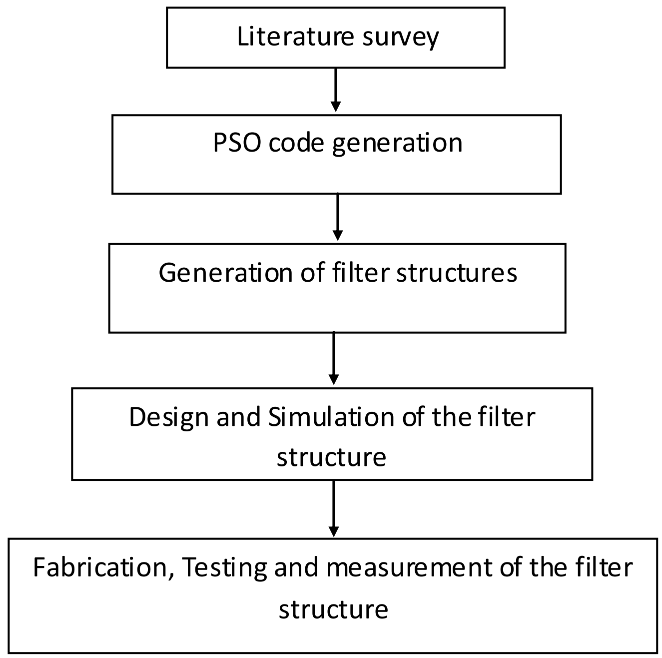


Figure 1: Schematic flow diagram of the proposed method

Code development for Particle swarm optimization:

PSO is relatively a novel approach for global stochastic optimization. In this method, the population dynamics simulate the behavior of a 'bird's flock', where social sharing of information takes place and individuals profit from the discoveries and previous experience of all other companions during the search for food. Thus, each companion, called particle, in the population, or swarm, is assumed to 'fly' over the search space looking for promising regions on the landscape.

It simulates basically the function of a swarm, or flock, of beings wandering in the parameter space and is based on a 'social interaction' metaphor in which the path of the beings in the parameter space is controlled according to a swarm- or flock-like set of rules. The position of each particle is used to compute the value of the function to be optimized. Individual particles are then attracted, with a stochastic-varying strength, by both the position of their best past performance and the position of the global best performance of the whole swarm

In PSO, each particle represents an alternative solution in the multidimensional search space. Thus these particles are multi-dimensional vectors whose trajectories are updated based on the velocity defined by its previous best success, pbest, and the best success achieved by the best particle in the swarm, gbest.

The velocity and position of the particles are updated based on the following equations:

$$v_{i,n}(t+1) = wv_{i,n}(t) + c_1 r_1 \left[p_{best} - x_{i,n}(t)\right] + c_2 r_2 \left[g_{best} - x_{i,n}(t)\right] \tag{1}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{2}$$

where $x_{i,n}(t)$and $v_{i,n}(t)$ are the current location and velocity vector of the i^{th} particle in its n^{th} dimension. w is the inertia weight used to control global exploration and local exploitation of the particles, and is usually varied linearly from 0.9 to 0.4 in a decreasing order throughout the simulation, c_1 and c_2 are the acceleration constants that act as weights to provide the relative pull for each particle towards p_{best} and g_{best} positions. r_1 and r_2 are two uniformly distributed random variables in the range [0,1] to provide a stochastic variation in the relative pull towards p_{best} and g_{best}. The velocities are in between ± v_{max} of all particles in the population, in the D-dimensional search space, where

$$v_{max} = 0.25\left(x_{max} - x_{min}\right) \tag{3}$$

In most cases, the parameters v_{max} ,v_{min} that act as an upper and lower limits respectively for the achievable velocity of the particles. They are also used to control the ability of the particles to search and be confined within the search space. In the i^{th} iteration, d^{th} dimension, the $v_i(d)$ is calculated by

$$v_i(d) = \min\left(v_{max}(d), \max\left(-v_{max}(d), v_i(d)\right)\right) \tag{4}$$

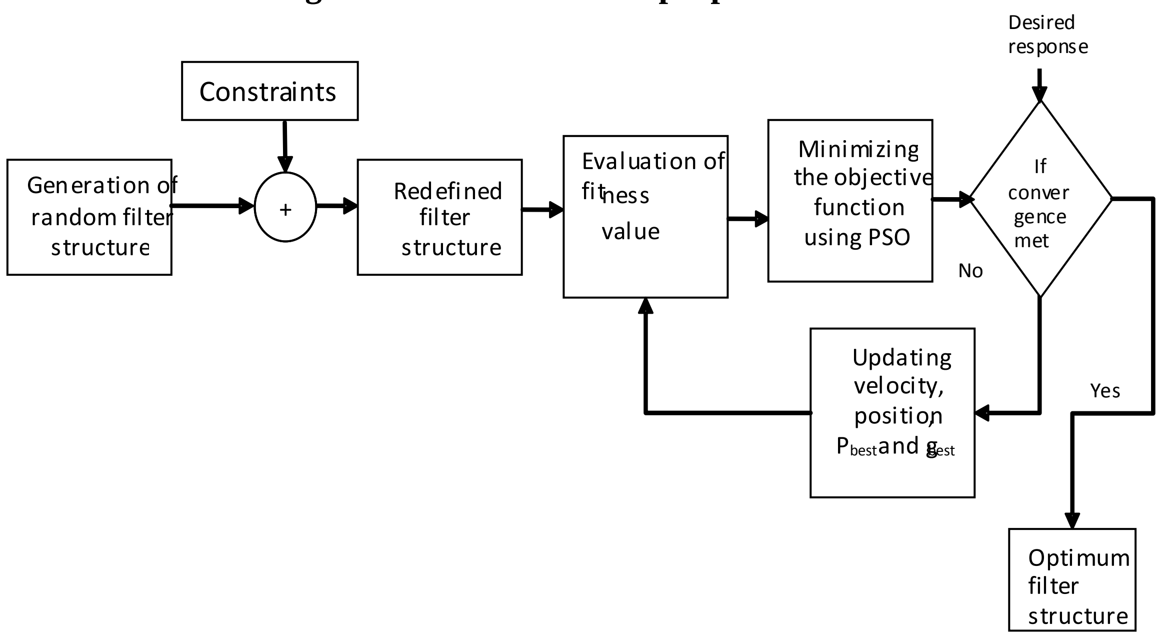
However, it has been noted that the particles may still occasionally fly to a position beyond the search space, and hence produce an invalid solution. The inertia value, w, is updated in all iterations by the equation as is taken from Baskar (Baskar et al 2005). The inertia weight value for i^{th} iteration is calculated by

$$w(i) = \frac{(w_0 - 0.2) \times (\max\_iter - i)}{\max\_iter} + 0.2 \text{ , where } w_0 = 0.9, \tag{5}$$

This algorithm is iterated until the convergence criterion is met when the evaluation count reaches the maximum value or one of a particle in the group reaches the minimum fitness value i.e., zero.

Figure 2 illustrates the flowchart of the proposed PSO algorithm. The first step is to generate '*n*' random particles satisfying all constraints. The initial position values of the particle are taken as such. The initial best positional values within the particles and the global positional values within the initial iteration are found. Following this the fitness value of every constraint satisfied particle are evaluated. If the fitness value reaches the convergence criterion such as iteration count reaches the maximum value or the fitness value either reaches the minimum value or close to zero, then the optimum particle is identified. Otherwise, the algorithm is iterated continuously with the change in position and velocity values that will change the local best and global best values.

Figure 2 Flowchart of the proposed method



PSO for Microwave Filter Design

A novel PSO based filter synthesis procedure is proposed as a suitable alternative of the conventional design and modeling approaches. The proposed PSO approach is capable of searching the filter structure and its corresponding electrical parameters directly from the desired response.

- **Design procedure**

The PSO based filter synthesis approach consists of formation of filter structure, calculation of S-parameter, generation of fitness function with constraints, evaluation of fitness value and minimization of fitness value using PSO (Figure 3).

Formation of Filter structure

↓

Calculation of S-Parameter

↓

Generation of the objective function with constraints

↓

Evaluation of Fitness value using PSO

↓

Selection of Optimum filter structure

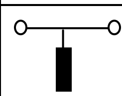
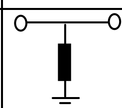
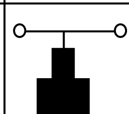
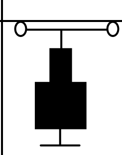
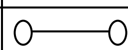
Figure 3 Schematic diagram of the proposed method

1 Formation of Filter structure

To start with, an arbitrary filter structure is formed with the help of transmission line elements, as shown in Figure 4 (Ming-Iu Lai and Shyh-Kang Jeng 2006). The type of transmission line, the mode of connection with the neighboring circuit elements and the electrical parameters of the corresponding elements are shown in Table 1. Null is a special element used to describe a circuit with an arbitrary filter orders.

In this approach an arbitrary two-port network can be used to represent a set of filter structures, Figure 4 (a), in matrix form. A matrix 8 x 6 shown in Figure 4(b) represents the filter structure considered.

Table 1 Basic filter elements

Type	**Name**	**Network topology**	**Connection**	**Electrical parameters**	**Limits of Z_{01} and Z_{02} in Ω**	**Limits of θ_1 and θ_2 in °**
0	**TL**		Cascade	Z_{o1} θ_1	67-110	30-100
1	**Sh_TL_OC**		Cascade	Z_{o1} θ_1	67-110	20-160
2	**Sh_TL_SC**		Cascade	Z_{o1} θ_1	67-110	20-160
3	**Sh_TL2_OC**		Cascade	Z_{o1} θ_1 Z_{o2} θ_2	67-110	20-120
4	**Sh_TL2_SC**		Cascade	Z_{o1} θ_1 Z_{o1} θ_2	67-110	20-120
5	**Null**		0	0 0	0	0

Z_{o1}, Z_{o2} – Characteristic impedance of the transmission line sections.
θ_1, θ_2 -- Electrical length of the transmission line section at f_o, degrees.

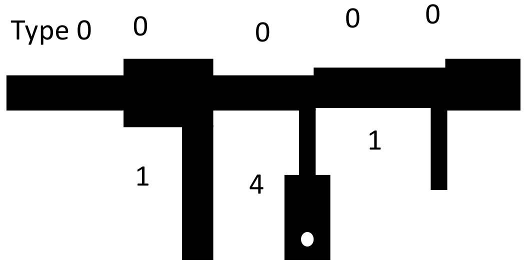


Figure 4(a) Basic filter structure

Connection approach
0: Cascade connection
1: Parallel connection

Corresponding electrical parameters

Describing a filter element

$$\text{Filter structure} = \begin{pmatrix} 0 & 0 & 65.2 & 62.4 & 0 & 0 \\ 0 & 0 & 23.5 & 45.7 & 0 & 0 \\ 1 & 0 & 25.13 & 70.2 & 0 & 0 \\ 0 & 1 & 41.5 & 32.7 & 0 & 0 \\ 4 & 0 & 80.4 & 48.9 & 38.1 & 26.2 \\ 0 & 0 & 53.5 & 72.7 & 0 & 0 \\ 1 & 0 & 75.13 & 62.2 & 0 & 0 \\ 0 & 0 & 18.5 & 81.7 & 0 & 0 \end{pmatrix}$$

Figure 4(b) Matrix representation of a filter structure

In Figure 4(b), the first column illustrates the type of filter element, second column represents the way of connection and other columns are used to represent their electrical parameters.

2 Calculation of S-Parameter

The ABCD-matrix T_1 for a (type 0) transmission line with characteristic impedance Z_1 and electrical length θ_1 is (Pozar 1998).

$$T_1 = \begin{bmatrix} \cos\theta_1 & jZ_1 \sin\theta_1 \\ j\dfrac{\sin\theta_1}{Z_1} & \cos\theta_1 \end{bmatrix} \tag{6}$$

The ABCD-matrix T_2 represents the short-circuited stub section (type 2) as

$$T_2 = \begin{bmatrix} 1 & 0 \\ j\dfrac{1}{Z_2 \tan\theta_1} & 1 \end{bmatrix} \tag{7}$$

For an example eight element band pass filter structure, as shown in Figure 3(a), the ABCD parameter of this filter structure is given as

$$T = \prod_{i=1}^{8} T_i = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{8}$$

The transmission coefficient value (S_{21}) of a structure is obtained from the resultant ABCD values and is given by

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{9}$$

3 Generation of the objective function with constraints

The design problem can be written as

$$P^* = \arg\left(\min_P F\left(S\left(P\right)\right)\right) \tag{10}$$

where 'P' is the filter structure which acts as a particle in the PSO, $S(P)$ is the simulated scattering parameter of the particle $F(\cdot)$ is the fitness function and P^* is the optimum particle. The fitness function (F) is given by (Ming-Iu Lai and Shyh-Kang Jeng 2006)

$$F = \sum_{j=1}^{N} w_j f_j \tag{11}$$

where w_j is the weighting value at the j^{th} sampling point, $f_j = \left(d_j - S_j\right)^2$ and d_j and S_j are the magnitude of the desired and simulated scattering parameters at the j^{th} sampling point respectively. Constraints for the fitness function in the synthesis of filters are that primarily, the electrical parameters must lie within the lower and upper limits so that the fabrication issues and discontinuity effects are reduced. Secondly, the stubs have to be connected in cascade such that the junctions are to be either step-, tee- or cross-junctions and other than these, the lines cannot be realized practically. Finally, the location of transmission zeros must be defined clearly so that the time required for computation of frequency response is reduced.

For a filter structure with an open- or short-circuited shunt stub, the location of zeros can be determined by

$$f_n = \frac{(2n-1)}{2}\frac{\pi}{\theta} f_0 \text{ (for type Sh\_TL\_OC)} \tag{12a}$$

$$f_n = (n-1)\frac{\pi}{\theta} f_0 \text{ (for type Sh\_TL\_SC)} \tag{12b}$$

$$f_n \cong \frac{(2n-1)}{2}\frac{\pi}{\theta_1 + \theta_2} f_0 \text{ (for type Sh\_TL2\_OC)} \tag{12c}$$

$$f_n \cong (n-1)\frac{\pi}{\theta_1 + \theta_2} f_0 \text{ (for type Sh\_TL2\_SC)} \tag{12d}$$

where θ, θ_1, and θ_2 are the electrical length of the stubs in radians, f_0 denotes the reference frequency, and $n = 1,2, \ldots$.

Figure 5 illustrates the non-feasible junction of the microwave filter elements. The filter elements 3, 4, 6 and 7 creates a cross junction.

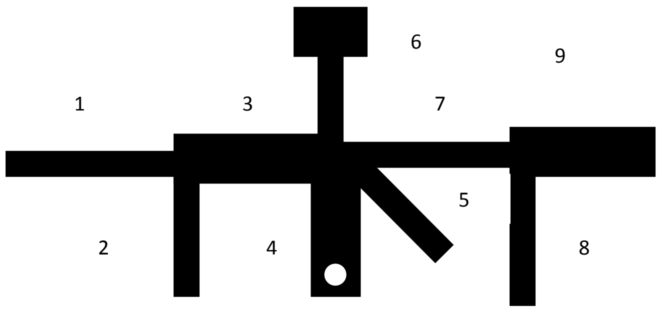


Figure 5 Illustration of the step, tee, cross and other junctions of the filter structure

4 Evaluation of Fitness value using PSO

- The next step in the filter synthesis of a proposed method is to optimize the fitness function using PSO. All particles have positions representing possible solutions that are evaluated by the fitness function formed by the problem to be optimized and velocities that direct the flying of the particles for better convergence. The first step for this is to generate '*n*' arbitrary filter structures namely the particles satisfying the constraints. The S-Parameter and fitness value of all particles are evaluated using equations (9) and (11) respectively.
- In PSO, each particle represents an alternative solution in the multidimensional search space. Thus these particles are multi-dimensional vectors whose trajectories are updated based on the velocity defined by its previous best success, p_{best}. The best success is achieved by the best particle in the swarm, g_{best}.
- The position of the particle is related with the characteristic impedance and electrical length of the filter structure and the velocity is related with the step change value of the same parameters for all iterations. Then the velocity and

position of the particles are updated by the equations (1) and (2) (Mandal and Arijit De 2005).

Filter design and testing report

Develop a structure for dual band filter:

- To show the validity of the proposed PSO based filter synthesis methodology, a set of band pass filters representing various orders in a chosen wireless band is designed. A dual-band band-pass filter with the first centre frequency at 3.5GHz (fc), second center frequency at 5.5 GHz, bandwidth of 200 MHz having near 0 dB insertion loss in the pass band and 20dB rejection in the transition bands of 2 to 3 GHz, 4 to 5 and 6 to 7 GHz is considered. Initially one lakh dual-band band-pass filters with various orders are generated. The filter structure consists of several basic filter elements which were taken from the Table 1.
- The filter structure thus formed is represented by a matrix form, 10 x 6, as its size is maintained by the null element of the filter structure. From this formed filter structures only ten structures/particles satisfied the constraints. The electrical parameters of the filter structures are generated for the given specifications, using Table 1, that are taken as the initial particle position of the PSO. The electrical parameter values are changed iteratively with respect to the obtained Zpbest, Zgbest, θpbest and θgbest.
- The fitness value of the filter structures are calculated using equation (13).

$$P^{*} = \arg\left(\min_{P} F\left(S\left(P\right)\right)\right) \tag{13}$$

The fitness value fully depends on the selection of weight value. The impedance values and electrical lengths of the filter structures are optimized using equations

(1) and (2) until the evaluation count reaches the maximum value or one of a particle in the group reach the target fitness value zero or close to zero.

- The proposed PSO algorithm has been implemented in MATLAB environment. The fitness value of the optimum filter structure satisfying the specification is found to be 0.1017. The time taken for obtaining the converged filter structure solution is 102.2 seconds. The rate of convergence is shown in Figure 6. It can be seen from the figure, that the sharp glitches are automatically removed by the inertia weight values which was calculated by the equation (2). For the chosen specification the optimum filter structure has three transmission lines and seven open circuited shunt stubs. Filter elements and its electrical parameters of the optimum filter structure are given in Table 2.

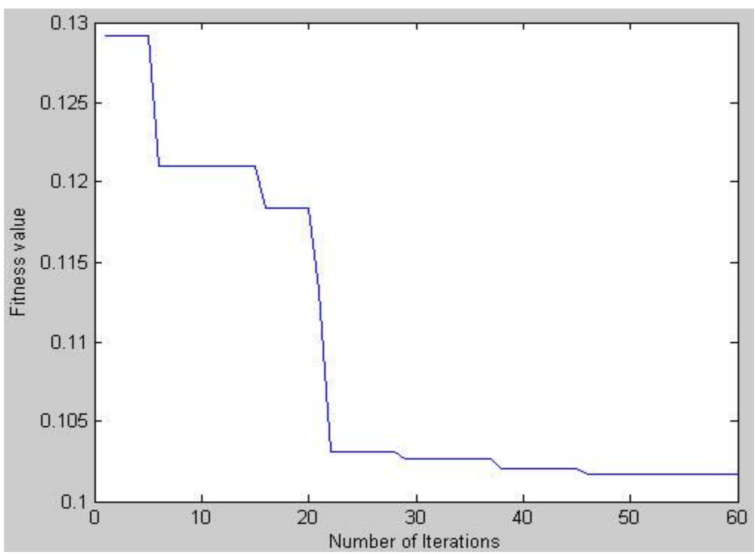


Figure 6 Fitness value versus Number of Iterations curve for PSO based band pass filter

Table 2 Optimum filter structure and their electrical parameters using PSO

Type	Impedance (Ω)	Electrical length (˚)	Impedance (Ω)	Electrical Length (˚)
Sh_TL2_OC	**100.14**	**105.12**	**71.97**	**89.9**
Sh_TL_OC	**87**	**92.3**	**0**	**0**
TL	**57.8**	**91.64**	**0**	**0**
Sh_TL_OC	**108.08**	**87.04**	**0**	**0**
Sh_TL2_OC	**101.07**	**73.6**	**65.05**	**194.7**
TL	**65**	**76.35**	**0**	**0**
Sh_TL2_OC	**71.5**	**49.42**	**0**	**0**
TL	**60.2**	**102.57**	**0**	**0**
Sh_TL_OC	**60.59**	**161.7**	**0**	**0**
Sh_TL_OC	**71.0**	**56.71**	**0**	**0**

- **Evaluation of the method:**

Table 3 Optimum structure and their electrical parameters for single band bandpass filter using PSO

Type	Impedance (Ω)	Electrical length (˚)	Impedance (Ω)	Electrical Length (˚)
Null	---	---	---	---
Null	---	---	---	---
Sh_TL_OC	85.89	91.36	0	0
Sh_TL_OC	55.3	131.5	0	0

Null	---	---	----	----
TL	45.8	127.76	0	0
Sh_TL_OC	103.5	61.35	0	0
Sh_TL2_OC	42.9	80.8	54.7	90.9
TL	60.1	137.2	0	0
Sh_TL_OC	109.2	147.6	0	0

- The optimum filter structure obtained from the PSO technique is simulated using the simulation software ADS2002C. Basic filter elements like TL, Sh_TL_OC, Sh_TL_SC, Sh_TL2_OC and Sh_TL2_SC are joined together to form the final filter structure. The layout of the filter structure is shown in Figure 7.

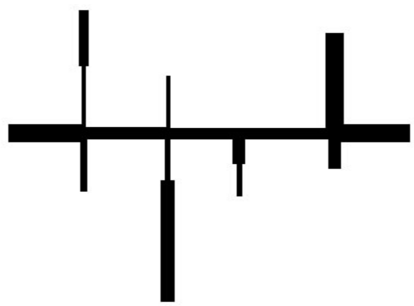


Figure 7 Layout of the optimum filter structure using PSO

- The optimized filter layout is fabricated on a glass epoxy substrate with a dielectric constant (ε_r) of 4.6 and a thickness of 1.6 mm, as shown in Figure 8 and its RF performance is measured using the Agilent N5230A vector network analyzer.

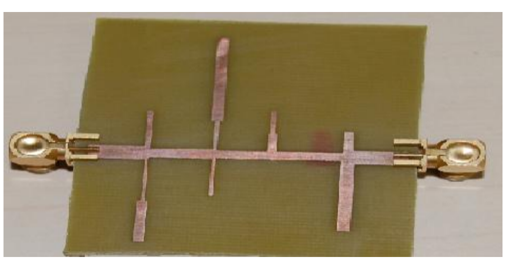


Figure 8 Photograph of the fabricated PSO based dualband band pass filter

The insertion and return loss versus frequency are shown in Figure 9(a) and (b). For the simulated model, the insertion loss of less than 2 dB in the required first and second passband of 200MHz, the return loss of 15.5 dB at the first center frequency and 35 dB at the second center frequency. The measured response is shown in Figure 5.5(b). The measured insertion loss within the pass band is around 5 dB and return loss is 35 dB at the first pass band and insertion loss within the pass band is around 7 dB and return loss is 15 dB at the second pass band. It is to be noted from Figure (b), the insertion loss of the filter is around 5 dB in the pass band, due to the different types of filter elements which are connected together lead to discontinuity effect. The computational time required for the selection of optimum filter structure is less, roughly 102 sec. as compared to 7.0 hours taken for particle generation with constraint.

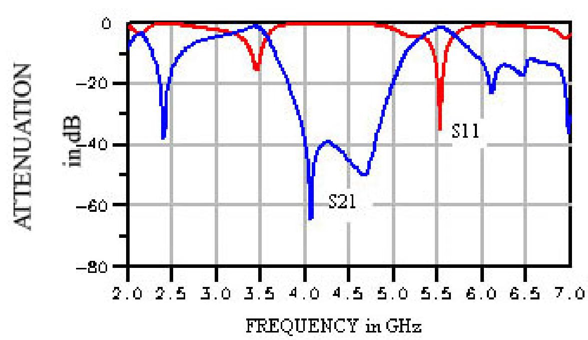


Figure 9(a) **S_{11} and S_{21} versus frequency of the simulated PSO based dual band filter**

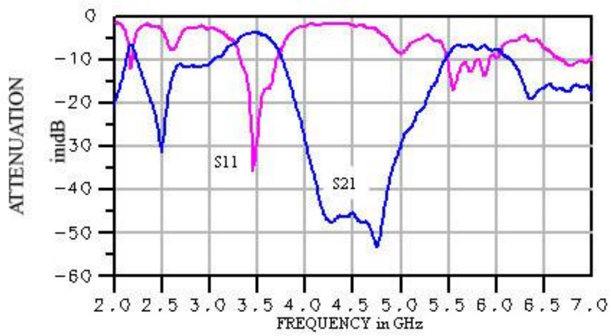


Figure 9(b) S_{11} **and** S_{21} **versus frequency of the fabricated PSO based dual band filter**

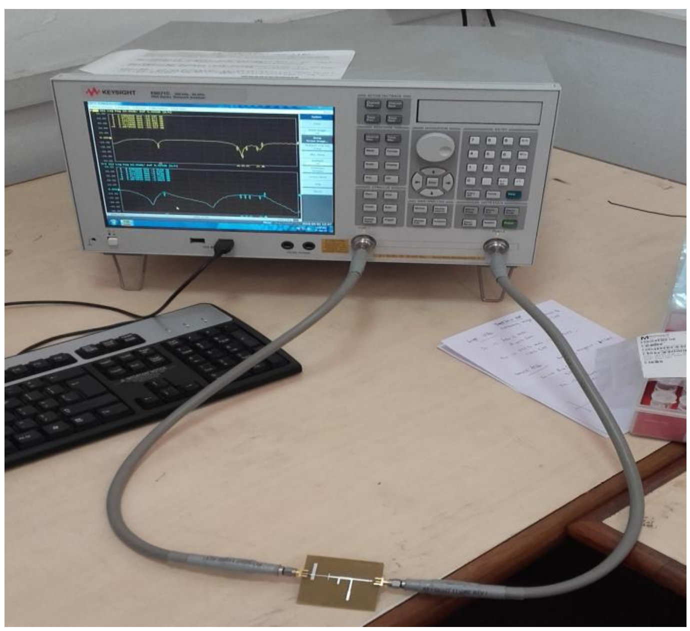


Figure 10(a) S_{11} **and** S_{21} **versus frequency of the fabricated PSO based dual band filter for 2.5 and 5.3 GHz bands**

Figure 10(b) S_{11} and S_{21} versus frequency of the fabricated PSO based dual band filter for 2.5GHz and 5.3 GHz bands

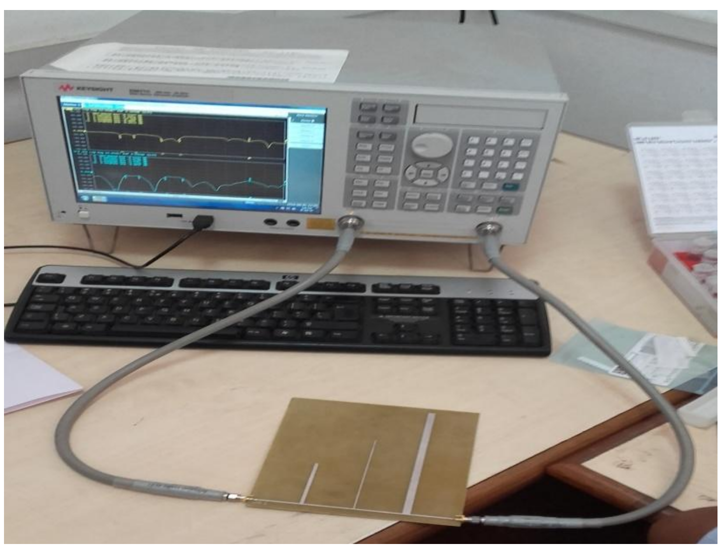


Figure 11(a) S_{11} and S_{21} versus frequency of the fabricated PSO based dual band filter for 890 MHz and 1.5 GHz

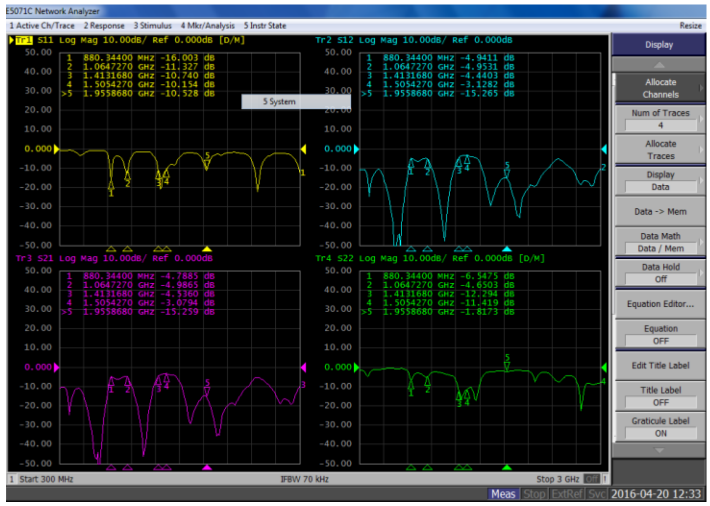


Figure 11(b) S_{11} and S_{21} versus frequency of the fabricated PSO based dual band filter for 890 MHz and 1.5 GHz

LIST OF PUBLICATIONS

S. No	Title	Journal/Conference	Details
1	Synthesis of dualband band pass filter using multi objective PSO	ARPN (Asian Research Publishing Network) Journal of Engineering and Applied Sciences	ISSN No: 1819-6608, Volume 10, No.21, November 2015.

Annexure – IX

UNIVERSITY GRANTS COMMISSION
BAHADUR SHAH ZAFAR MARG
NEW DELHI – 110 002

PROFORMA FOR SUBMISSION OF INFORMATION AT THE TIME OF SENDING THE FINAL REPORT OF THE WORK DONE ON THE PROJECT

1. Title Of The Project	Synthesis of Dualband Bandpass filter Using Particle Swarm Optimization technique for Wireless application
2. Name And Address Of The Principal Investigator	Dr.A Thenmozhi
3. Name And Address Of The Institution	Thiagarajar College of Engineering, Madurai-625015
4. Ugc Approval Letter No. And Date	F. No. 41-605/2012 (SR) and 17-07-2012
5. Date Of Implementation	01.07.2012
6. Tenure Of The Project	3 Years 6 Months
7. Total Grant Allocated	Rs.7,49,319/-
8. Total Grant Received	Rs.6,89,267/-
9. Final Expenditure	Rs.6,93,713/-
10. Objectives Of The Project	• To develop a novel synthesis procedure for the design of microwave band pass filter with stringent requirements such as small size, high performance means sharp cutoff, low insertion loss in the pass bands, and better out-of-band rejection. • To design a dual-band filter with transmission zeros of the required bands.
11. Whether Objectives Were Achieved (Give Details)	Yes. Emerging wireless communication systems demand microwave filters with stringent roll off characteristics. In the conventional microwave filter synthesis procedure, one starts with the desired design specifications and arrives at an initial configuration based on the chosen insertion loss method. The filter approximations generate the rounded off order and values of the lumped prototype filter which is then scaled with respect to the required frequency and impedance. Based on this, a novel synthesis procedure is developed for the design of microwave band

	pass filter with stringent requirements such as high performance means sharp cutoff, low insertion loss in the pass bands, and better out-of-band rejection. In this proposed methodology, Particle Swarm Optimization technique is used to identify the filter structure, without manual interruption. The dual-band band pass filter consists of two single-band band pass filters operating at the upper band and the lower band which can be simply connected to achieve the desired dual-band band pass filter, although tuning between the two single band filters is very difficult and size of the filter is also increased. This proposed method eliminates this difficulty with the help of transmission zeros. Transmission zeros are at 4.0 GHz, 2.0 GHz, 6GHz, 1.5 GHz and 2.4 GHz Time taken to converge the filter structure is 102.2 seconds.
12. Achievements From The Project	• One Journal Publication – Asian Research Publishing Network (ARPN) Journal of Engineering and Applied Sciences • One PG project done
13. Summary Of The Findings (In 500 Words)	Tuning between the two single band filters is Eliminated. Hence design time is reduced for dualband filter.
14. Contribution To The Society (Give Details)	Nil
15. Whether Any Ph.D. Enrolled/Produced Out Of The Project	Nil
16. No. Of Publications Out Of The Project (Please Attach)	One (attached)

PRINCIPAL INVESTIGATOR)

REGISTRAR/PRINCIPAL

PRINCIPAL
Thiagarajar College of Engineering
Madurai - 625 015

THIAGARAJAR COLLEGE OF ENGINEERING MADURAI 625 015

VOL. 10, NO 21, NOVEMBER, 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

SYNTHESIS OF DUALBAND BAND PASS FILTER USING MULTI OBJECTIVE PSO

A. Thenmozhi
Thiagarajar College of Engineering, India
E-Mail: thenmozhi@tce.edu

ABSTRACT

A novel synthesis procedure for the design of microwave dualband bandpass filter using multi objective Particle Swarm Optimization (PSO) for 3.5 GHz and 5.5GHz Wimax applications is presented in this paper. This filter provides an insertion loss within the pass band is around -5 dB and return loss is -35 dB at the first pass band and insertion loss within the pass band is around -7 dB and return loss is -15 dB at the second pass band.

Keywords: dualband, bandpass filter, multiobjective, particle swarm, microwave filter, Wimax.

INTRODUCTION

Multiple frequency bands are necessary for reducing the number of components and size of the modern wireless communication applications. Recently wireless communication systems have increased demand for compact and multifunctional and multiband microwave filters. Two or more single band filters are combined together to form a dualband or multiband filter respectively. However, the size of the filter is increased and tuning between them is critical. Hence, a single filter having two pass bands in desired locations is intricate.

Several structures have been developed for achieving dualband filters [1-9], during 2000s and 2006s, using UIR, SIR, OLRR, combline and hairpin structures. Another approach is to cascade a band pass filter with a band stop filter, requires an additional matching network to connect them [10].

The synthesis of a microwave filters with the selection of transfer function that fulfills the electrical specifications such as low insertion loss, good flatness high rejection level, size and cost. This methodology is very attractive for planar filters because of reduced bulk and low production cost. Moreover, the location of the transmission zero is controlled on either side of the pole [11-13]. Unfortunately, more attention is required to eliminate the spurious harmonics on either side of the side band [13]. Low frequency spurious response is eliminated by short circuited stubs, due to via holes complexity is increased, and open circuited Capacitive coupled structure, getting desired value of capacitance is difficult. Another method is to place zeros on either side of the pole using robust optimization techniques. Reduction of spurious response is searching the optimal electrical parameters of a given circuit topology, although convergence is not guaranteed for high selectivity requirements. Genetic algorithm has been used to synthesize dual band band pass filter using circuit topology as well as corresponding electrical parameters [14]. However, the genetic operators such as choice, crossover and mutation are relatively complex and more space is required [15]. To overcome this, a relatively original approach for global stochastic optimization is Particle Swarm (PS). Particle Swarm Optimization (PSO) is similar to Genetic Algorithms (GA) for performing a global search in the parameter space but does not get trapped in local minima.

In most real world problems multi objective (MO) optimization is very common. Twoor more, sometimes competing and/or incommensurable fitness functions have to be minimized simultaneously [16]. The objective functions may be in conflict, thus, in most cases it is impossible to obtain for all objectives the global minimum at the same point. The goal of MO is to provide a set of optimal solutions to the aforementioned problem [17]. This paper proposes a novel PSO based synthesis procedure for a class of dual band bandpass filters using multi objective technique.

METHODOLOGY

Arbitrary filter structures, satisfying the constraints, are formed with the help of transmission line elements [18]. The type of transmission line, the mode of connection with the neighboring circuit elements and the electrical parameters of the corresponding elements are shown in Table-1.

VOL. 10, NO 21, NOVEMBER, 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-1. Basic filter elements.

Type	Name	Network topology	Connection	Electrical parameters
0	TL		Cascade	$Z_{o1}\ \theta_1$
1	Sh_TL_OC		Cascade	$Z_{o1}\ \theta_1$
2	Sh_TL_SC		Cascade	$Z_{o1}\ \theta_1$
3	Sh_TL2_OC		Cascade	$Z_{o1}\ \theta_1\ Z_{o2}\ \theta_2$
4	Sh_TL2_SC		Cascade	$Z_{o1}\ \theta_1\ Z_{o1}\ \theta_2$
5	Null		0	0 0

Zo1, Zo2 - Characteristic impedance of the transmission line sections. θ_1, θ_2 are denoted Electrical length of the transmission line section at f0, degrees.

A typical filter structure is shown in Figure-1. Null is a special element used to describe a circuit with an arbitrary number of basic circuit elements and orders.

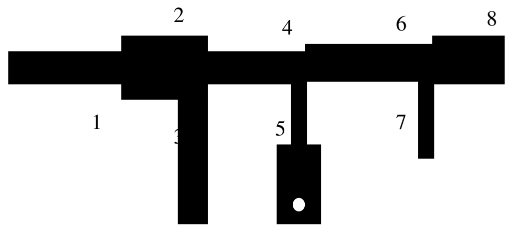


Figure-1. Basic filter structure.

The Scattering matrix of the filter structure plays major role in the evaluation of fitness value. The scattering parameter of each filter structure is calculated from the ABCD parameters. ABCD parameters of the single filter element are decided by their electrical parameters [19]. ABCD-matrix T_1 for a transmission line by characteristic impedance Z_1 and electrical length θ_1 is

$$T_1 = \begin{bmatrix} \cos\theta_1 & jZ_1 \sin\theta_1 \\ j\dfrac{\sin\theta_1}{Z_1} & \cos\theta_1 \end{bmatrix} \tag{1}$$

The ABCD-matrix T_2 represents the short-circuited stub section as

$$T_2 = \begin{bmatrix} 1 & 0 \\ j\dfrac{1}{Z_2 \tan\theta_1} & 1 \end{bmatrix} \tag{2}$$

The entire ABCD parameter is the multiplication of individual element's ABCD parameter. For an example eight element band pass filter structure is shown in Figure-1. The ABCD-matrix of the whole structure is

$$\boldsymbol{T} = \prod_{i=1}^{8} \boldsymbol{T}_i \tag{3}$$

The S-Parameter value of a structure is obtained from the resultant ABCD values as given by

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{4}$$

$$S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \tag{5}$$

With this scattering parameter value and the suitably selected weight values are used to calculate the fitness value for the constraint satisfied filter structures.

Let X be an n-dimensional search space and $f_i(x)$, $i = 1,\ldots,k$, be k objective functions defined over X [16]. Assuming, $g_i(x) \leq 0$, i= 1,... ,m, be m inequality constraints, the MO problem can be stated as finding a vector $x^* = (x_1^*, x_2^*, \ldots\ldots x_n^*) \in X$ that satisfies the constraints and optimizes (without loss of generality and

ARPN Journal of Engineering and Applied Sciences

consider only the minimization case) the vector function $f(x)=[f_1(x), f_2(x), ...f_k(x)]$.

According to this approach, the overall fitness value can be expressed by [17],

$$S=\left[\sum_{i=1}^{M}\left(W_i F_i\right)^2\right]^{\frac{1}{2}} \tag{6}$$

where W_i is the weighting value on the i^{th} fitness value, M is the number of fitness values, F_i is the i^{th} fitness value, and is given by

$$F_i=\sum_{j=1}^{k} w_j f_j\left(x\right) \tag{7}$$

Where w_j, $j = 1, \ldots, k$, are non-negative weights. These weights can be either fixed or dynamically adapted during the optimization [16].

Fitness sharing was introduced by Goldberg and Richardson (Goldberg and Richardson 1987), and applied successfully to a number of difficult and real world problems. The target of fitness sharing is to distribute the population over a number of different peaks in search space, with each peak receiving a fraction of the population in proportion to the height of that peak. To achieve this distribution, sharing calls for the degradation of an individual's objective fitness *fi* by a niche count, calculated for that individual. Then the shared fitness is [20, 21]

$$f_{share}(i)=\frac{f_{raw}(i)}{\sum_{j=1}^{a} Sh[d[i,j]]} \tag{8}$$

where *fraw (i)* is the fitness value of *i*th population which was not undergone the sharing function.

Fitness function with constraints

In this proposed method the design problem can be originated from

$$P^* = arg\left(\min_P F\left(S(P)\right)\right)$$
(9)

where P^* is the optimum particle, P denotes the particle of the PSO, *S(P)* is the simulated scattering parameter of the particle and *F* is the fitness function to be minimized. The fitness function (*F*), for the synthesis of microwave filter defines the error between the actual and the simulated response [5] is given by

$$F=\sum_{j=1}^{N} w_j f_j \tag{10}$$

where w_j is the weighting value at the j^{th} sampling point, $f_j=\left(d_j-S_j\right)^2$ and d_j and S_j are the magnitude of the desired and simulated scattering parameters at the j^{th} sampling point respectively. The weight values are chosen such that the fitness function is minimized. Constraints for this fitness function in the synthesis of filters are that the electrical parameters must lie within the lower and upper limits so that the fabrication issues and discontinuity effects are reduced, the stubs have to be connected in cascade if it is in parallel practical realization is difficult [19], junctions are to be either step-, tee- or cross-junctions other than these cannot be realized practically and the location of transmission zero must be defined clearly so that the time required to compute frequency response for a filter structure is reduced.

Evaluation of fitness function

The fitness function is minimized by a population based stochastic optimization method called PSO. Each solution in PSO is like a bird in the solution space, which is called particle. All particles have positions representing possible solutions that are evaluated by the fitness function formed by problems to be optimized, and velocities that direct the flying of the particles. The first step is to generate n number of random filter structures satisfying the constraints, called as particles. The S-Parameter and fitness value of all particles are evaluated using equations (4), (5) and (6) depends upon the requirement. In PSO, each particle represents an alternative solution in the multidimensional search space. The arbitrary filter structures formed are the particles in the PSO method. Thus these particles are multi-dimensional vectors whose trajectories are updated based on the velocity defined by its before best success, p_{best}, and the best success achieved by the best particle in the swarm, g_{best}. The velocity and position of the particles are updated based on the following equations:

$$v_{i,n}(t+1)=wv_{i,n}(t)+c_1r_1\left[Z_{pbest}-Z_{i,n}(t)\right]+c_2r_2\left[Z_{gbest}-Z_{i,n}(t)\right] \tag{11}$$

$$x_{in}(t+1)=x_{in}(t)+v_{in}(t+1) \tag{12}$$

where $x_{i,n}(t)$and $v_{i,n}(t)$ are the current location and velocity vector of the i^{th} particle in its n^{th} dimension.*w* is the inertia weight used to control global exploration and local exploitation of the particles and typically decreases linearly from 0.9 to 0.4 during a run, has provided

ARPN Journal of Engineering and Applied Sciences

improved performance in a number of applications [22]. c_1 and c_2 are the acceleration constants that act as weights to provide the relative pull for each particle toward p_{best} and g_{best} positions. r_1 and r_2 are two uniformly distributed random variables in the range [0,1] to provide a stochastic variation in the relative pull towards p_{best} and g_{best}. In most cases, a parameter V_{max} that acts as an upper limit for the achievable velocity of the particles is also used to control the ability of the particles to search and be confined within the search space. However, it has been noted in [23] that the particles may still occasionally fly to a position beyond the search space, and hence produce an invalid solution. Fitness value for this proposed filter synthesis method is zero. This algorithm is iterated until the evaluation count reaches the maximum value or one of a particle in the group reaches the target fitness value. The selection of the optimum filter structure depends upon the fitness value. Minimum or least fitness value provides the response of the filter structure which comes closer to the desired output that will provide the optimum filter structure.

VALIDATION OF THE PROPOSED METHODOLOGY

To show the validity of the proposed PSO based filter synthesis methodology, a set of band pass filters representing various orders in a chosen wireless band is designed. A dual-band band-pass filter with the first centre frequency at 3.5GHz (fc), second center frequency at 5.5 GHz, bandwidth of 200 MHz having near 0 dB insertion loss in the pass band and -20dB rejection in the transition bands of 2 to 3 GHz, 4 to 5 and 6 to 7 GHz is considered. To start with one lakh dual-band band-pass filters with various orders are generated. The filter structure consists of several basic filter elements which were taken from the Table-1. The formed filter structure is represented by a matrix form, 10x6, as its size is maintained by the null element of the filter structure. From this formed filter structures only ten structures/particles satisfied the constraints. The electrical parameters of the filter structures are generated for the given specifications, using Table I, that are taken as the initial particle position of the PSO. The electrical parameter values are changed iteratively with respect to the obtained Z_{pbest}, Z_{gbest}, θ_{pbest} and θ_{gbest}. The fitness value of the filter structures are calculated using equations (6), (7) and (10). The fitness value fully depends on the selection of weight value. The fitness sharing algorithm is used to cluster the fitness values, using equation (8), towards the dual band of the filter. The impedance values and electrical lengths of the filter structures are optimized using equations (11) and (12) until the evaluation count reaches the maximum value or one of a particle in the group reaches the target fitness value zero or close to zero.

The proposed PSO algorithm is coded in MATLAB. The fitness value of the optimum filter structure satisfying the specification is found to be 0.1017. The time taken for obtaining the converged filter structure solution, as given in Table II, is 102.2 seconds. The rate of convergence is shown in Figure-2. It can be seen from the figure, the sharp glitches that are seen and are automatically removed by the inertia weight values. For the chosen specification the optimum filter structure has three transmission lines and six open circuited shunt stubs. Filter elements and its electrical parameters of the Optimum filter structure are given in Table-2.

Table-2. Optimum filter structure and their electrical parameters using PSO.

Type	Impedance (Ω)	Electrical length (°)	Impedance (Ω)	Electrical length (°)
Sh_TL2_OC	100.14	65.12	52.97	89.9
Sh_TL_OC	100	92.3	0	0
TL	75	112.64	0	0
Sh_TL2_OC	108.08	107.04	40	94
TL	37.07	96.35	0	0
Sh_TL2_OC	71.5	49.42	98.2	41.8
TL	60.2	112.57	0	0
Sh_TL2_OC	100.14	65.12	52.97	89.9
Sh_TL_OC	81.0	121.71	0	0

The optimum filter structure obtained from the PSO technique is simulated using the simulation software ADS2002C. Basic filter elements like TL, Sh_TL_OC, Sh_TL_SC, Sh_TL2_OC and Sh_TL2_SC are joined together to form the final filter structure. The layout of the filter structure is shown in Figure-3.

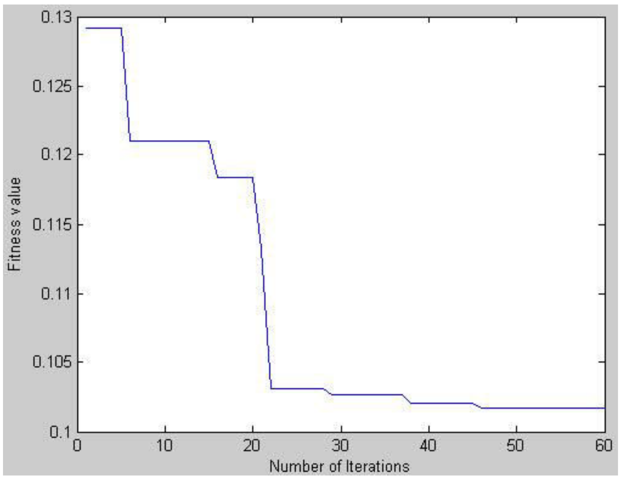


Figure-2. Convergence rate diagram for PSO based dual-band band pass filter.

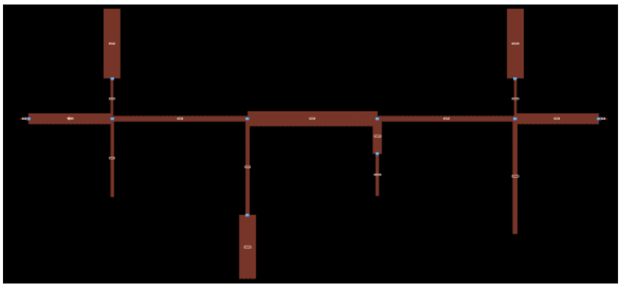


Figure-3. Layout of the optimum dual band bandpass filter structure.

The Insertion and return loss versus frequency are shown in Figure-4. For the simulated model, as shown in Figure-4(a), the insertion loss is < -2 dB in the required first and second pass bands of 200MHz, the return loss of -15.5 dB at the first center frequency and -35 dB at the second center frequency. The measured response is shown in Figure-5(b). The measured insertion loss within the pass band is around -5 dB and return loss is -35 dB at the first pass band and insertion loss within the pass band is around -7 dB and return loss is -15 dB at the second pass band. Insertion loss of the filter is around -5 dB in the pass band, due to the different types of filter elements which are connected together lead to discontinuity effect. It is also to be noted that time taken for the selection of optimum filter structure is less, roughly 102 sec. as compared to 7.0 hours taken for particle generation with constraint.

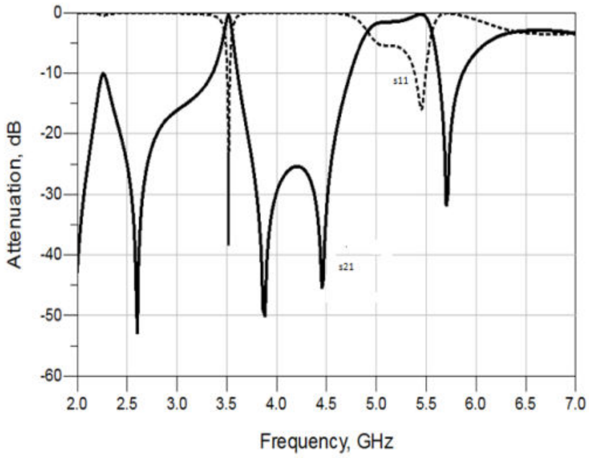


Figure-4(a). S11 and S21 responses of the simulated PSO based dual band filter.

CONCLUSIONS

This chapter proposes a novel and efficient synthesis method for a high performance dual band, multi objective band pass filter for wireless applications using PSO. The PSO has been used to model the distributed filter structure in terms of the scattering parameters. The proposed design approach is validated by simulation band pass filter on a microstrip platform using glass epoxy substrate. It is an efficient tool to design a filter but the insertion loss of the filter is high due to the discontinuity effect. It is to be noted that the fine tuning of the line dimensions is required to nullify the losses due to discontinuity.

REFERENCES

[1] Wada K. and Hashimoto O., "Fundamentals of open-ended resonators and their application to microwave filters", IEICE Trans. Electron. Vol. E83-C, pp. 1763-1775.

[2] Makimoto M. and Yamashita S., "Bandpass filters using parallel coupled stripline stepped-impedance resonators", IEEE Trans Microw. Theory Tech., Vol. MTT-28, No. 12, pp. 1413-1417.

[3] Chang S.F., Jeng Y.H. and Chen J.L., "Dual-band step-impedance band pass filter for multimode wireless LANs", Electron. Letters, Vol. 40, No. 1, pp. 38-39.

[4] Lee J., Uhm M.S. and Yom I.B, "A dual pass-band filter of canonical structure for satellite applications", IEEE Microwave and Wireless Component, Letters, Vol. 14, No. 6, pp. 271-273.

[5] KuoJ.T. and Shih E., "Microstrip stepped impedance resonator band-pass filter with an extended optimal rejection bandwidth", IEEE Trans. Microw. Theory. Tech. Vol. 42, No.7, pp. 1225-1230.

[6] KuoJ.T. and Cheng H.S., "Design of quasi - elliptic function filters with a dual pass band response", IEEE Microwave Wireless Components Lett., Vol. MTT-28, No. 10, pp. 472-474.

[7] Sun S. and Zhu L., "Compact dual-band microstrip bandpass filter without external feeds", IEEE Microw. Wireless Compon. Lett. Vol. 15, No. 10, pp. 644-646.

[8] Sun S. and Zhu L., "Coupling dispersion of parallel-coupled microstrip lines for dual-band filters with controllable fractional pass bandwidths", in IEEE MTT-S Int. Dig., pp. 2195-2198.

[9] Chen C. and Hsu C., "A Simple and Effective Method for Microstrip Dual-Band Filters Design", IEEE Microwave and Wireless Components, Vol. 16, No. 05, pp. 246-248.

[10] Tsai L.C. and Hsue C.W., "Dual-band bandpass filters using equal length coupled serial-shunted lines and Z-transform technique", IEEE Trans. Microw. Theory Tech., Vol. 52, No. 4, pp. 1111-1117.

[11] Hong J.S. and Lancaster M.J., "Novel slow-wave ladder microstrip line filters", European Microwave Conference, Vol. 26(1), pp. 431-434.

[12] Quendo C., Rius E. and Person C., "An original topology of dual-band filter with transmission zeros", IEEE MTT-S International Microwave Symposium Digest, Vol. 2, pp. 1093-1096.

[13] Quendo C., Rius E. and Person C., "Narrow bandpass filters using dual behavior resonators (DBRs) based on stepped-impedance stubs and different s-length stubs", IEEE Trans. Microw. Theory Tech., Vol. 52, No. 3, pp. 1034-1044.

[14] Nishino T. and Itoh T., "Evolutionary generation of microwave line segment circuits by genetic algorithms", IEEE Trans. Microwave, Theory Tech., Vol. 50, No. 9, pp. 2048-2055.

[15] Peik S.F. and Chow Y.L., "Genetic algorithms applied to microwave circuit optimization", in Proc. Asia-Pacific Microwave Conf., pp. 857-860.

[16] Parsopoulos K.E. and Vrahatis M.N., "Particle Swarm Optimization Method in Multi objective Problems", SAC 2002, Madrid, Spain, pp. 603-607.

[17] Ming-Iu Lai and Shyh-Kang Jeng, "Compact Microstrip Dual-Band Bandpass Filters Design Using Genetic-Algorithm Techniques", IEEE Trans. on Microwave Theory and Techniques, Vol. 54, No. 1, pp. 160-168.

[18] Thenmozhi A., Raju S. and Abhaikumar V., "PSO based Synthesis of Bandpass filter for WiMax Applications", International conference on soft computing techniques for industrial applications, Bhubaneswar.

[19] Pozar D. M., Microwave Engineering. New York: Addison-Wesley.

[20] Goldberg D.E., Genetic Algorithms in Search Optimization and Machine Learning. Reading, Addison-Wesley, MA.

[21] Goldberg D.E. and Richardson J.J., "Genetic algorithms with sharing for multimodal function optimization", Genetic algorithms and their applications: Proceedings of the Second ICGA, Lawrence Erlbaum Associates, Hillsdale, NJ, pp. 41-49.

[22] Kennedy J. and Eberhart R. C., "Particle swarm optimization", IEEE International Conference on Neural Networks, Piscataway, NJ. Vol. 4, pp. 1942-1948.

[23] S. Baskar, A. Alphones, P.N. Suganthan and J.J. Liang, "Design of Yagi - Uda antennas using comprehensive learning particle swarm optimization", IEE Proc.-Microwave Antennas Propag. Vol. 152, No. 5.