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DESIGN OF QUAD-BAND PASS FILTERS USING THREE-COUPLED FINLINE AND CONCENTRIC SPLIT RING RESONATORS

V. Madhusudana Rao*[1] and Dr. B. Prabhakara Rao[2]

[1]Senior Member IEEE, Department of Electronics and Communication Engineering, Jawaharlal Technological University, Kakinada, India- 532003.

[2]Senior Member IEEE, Former Rector of Jawaharlal Nehru Technological University, Kakinada, INDIA-532003.

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***Corresponding Author**
V. Madhusudana Rao
Senior Member IEEE, Department of Electronics and Communication Engineering, Jawaharlal Technological University, Kakinada, India- 532003.

ABSTRACT

This paper presents a new concept of a quad band pass filters with three parallel coupled finline structure and concentric split ring resonators. The finline is a wave guiding structure which is increasingly used as millimeter wave component due to various advantages such as reducing size, weight and cost. A design graph is presented here for symmetric three unilateral finline structures to design wide bandpass filter parameters like length (l), width (w) and spacing(s) between finlines. With these parameters we can design third order bandpass filter, having center frequency 10 GHz with fractional bandwidth of 20 %. This wide band pass filter is converted in to quad band pass filter with Metamaterials i.e. (Concentric Split Ring Resonators) on the other side of this filter structure substrate. The hypothesis of V.G. Veselago in 1968 that materials with simultaneous negative effective permittivity ε_{eff} **(**ω**)** and negative effective permeability μ_{eff} **(**ω**)** have unusual reversed electromagnetic wave propagation phenomena. The resonance frequency of these SRR can be adjusted by changing design parameters such as metal widths, gap distances for each ring as well as ring to ring separations. Modern communication transceivers require high performance microwave filters with low insertion loss, high frequency selectivity and small group delay variations. Most of the above said parameters are obtained with this proposed quad bandpass filter designed with three coupled finlines with metamaterials and this structure is suitable for millimeter wave components due to various advantages such as reducing size, weight and cost considerably. The suggested quad band pass filter structure is simulated in High Frequency Structure Simulator (HFSS).

KEYWORD: Metamaterial, Finline, Wide bandpass filter, Concentric Split Ring Resonators, Quad bandpass filters.

1. INTRODUCTION

Artificially structured metamaterials have generated enormous interest for their ability to display electromagnetic responses unavailable in conventional materials. Metamaterials in microwave field have been an object of great interest in recent past years. The hypothesis of V.G. Veselago in 1968 that materials with simultaneous negative effective permittivity ε_{eff} **(ω)** and negative effective permeability μ_{eff} **(ω)** have unusual reversed electromagnetic wave propagation phenomena.[1] Naturally occurring materials universally have a positive permeability and thus a Left-Handed Material (LHM), while not ruled out by fundamental considerations, seemed unlikely to be practical. However, in 1999, Pendry[2] et al, introduced several configurations of conducting scattering elements displaying a magnetic response to an applied electromagnetic field when grouped in to an interacting periodic array. SRR creates negative effective permeability $\mu_{\mathbf{eff}}$ (ω) over a particular frequency region and wire elements to produce negative effective permittivity ε_{eff} **(ω)** in an intersecting frequency region. The patterned arrays in magnetic metamaterials are typically planar conducting split ring resonators [SRRs], in which circulating currents are induced in response to the incident time-varying magnetic field. SRRs are made resonant by the inclusion of a capacitive gap, enabling SRR structures to exhibit relatively large positive and negative values of effective permeability. The finline is transmission line viz. metallic strips etched on substrate embodied in the trunk of the standard rectangular wave guiding structure which is increasingly used as millimeter wave component due to various advantages such as reducing size, weight and cost. At millimeter wave frequency the finline filter has been implemented in[1-6] which are mostly based on ladder/cascaded shape. This paper presents a Chebyshev filter of order 3 with fractional bandwidth 20% has been designed on RT-Duroid 5880™ substrate using unilateral three coupled finline. The advantage of this filter is low loss and wider bandwidth over the ladder/cascaded type filter. Metamaterials is a very interesting concept for converting this wide band pass filter into more band pass filters for effective utilization this band width. Now a days wireless multipurpose communication services are very much required to meet various applications. Need of multi band pass filters are very prominent to meet these requirements. This concept leads to design this quad band pass filter with finline transmission lines and Metamaterials (Concentric SRR).

2. ANALYSIS OF THREE COUPLED UNILATERAL FINLINES

The dispersion characteristics of multiple coupled unilateral finlines on isotropic substrate have been evaluated by using full wave modal analysis as shown in Fig.1. In this modal analysis, all the field components are constructed in terms of x-components of electric and magnetic fields in each region, which are expanded in terms of modal fields with unknown coefficients, are given below.

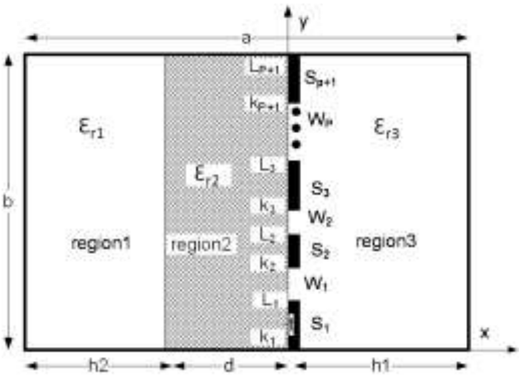


Fig. 1: Cross-section view of multiple edge coupled unilateral fin-line on isotropic substrate.

The Maxwell equation is

$$\begin{bmatrix} E_t \\ H_t \end{bmatrix} = \frac{1}{\left(k_o^2 \varepsilon_r - k_x^2\right)} \begin{bmatrix} \partial/\partial x & j\omega\mu_o x \\ -j\omega\varepsilon_o\varepsilon_r x & \partial/\partial x \end{bmatrix} \begin{bmatrix} \nabla_t E_x \\ \nabla_t H_x \end{bmatrix}. \quad (1)$$

The x-component of the electric and magnetic fields satisfy the Helmholtz equation

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \left(k_o^2 \varepsilon_r - \beta^2\right)\right] \begin{bmatrix} E_x \\ H_x \end{bmatrix} = 0. \quad (2)$$

Here side walls are considered to be electric walls.

Solutions of the equations in the three regions are,

$$E_x^{(1)} = \sum_{n=1}^{\infty} A_{n1} Cos\left[\Gamma_{n1}(x - h_1)\right] Sin(\alpha_n y) e^{-j\beta z}, \quad (3)$$

$$H_x^{(1)} = \sum_{n=0}^{\infty} B_{n1} Sin\left[\Gamma_{n1}(x - h_1)\right] Cos(\alpha_n y) e^{-j\beta z}, \quad (4)$$

$$E_x^{(2)} = \sum_{n=1}^{\infty}\left[A_{n2}Sin(\Gamma_{n2}x) + A'_{n2}Cos(\Gamma_{n2}x)\right]Sin(\alpha_n y)e^{-j\beta z}, \quad (5)$$

$$H_x^{(2)} = \sum_{n=0}^{\infty}\left[B_{n2}Cos(\Gamma_{n2}x) + B'_{n2}Sin(\Gamma_{n2}x)\right]Cos(\alpha_n y)e^{-j\beta z}, \quad (6)$$

$$E_x^{(3)} = \sum_{n=1}^{\infty} A_{n3}Cos\left[\Gamma_{n3}(x+d+h2)\right]Sin(\alpha_n y)e^{-j\beta z}, \quad (7)$$

$$H_x^{(3)} = \sum_{n=0}^{\infty} B_{n3}Sin\left[\Gamma_{n3}(x+d+h2)\right]Cos(\alpha_n y)e^{-j\beta z}, \quad (8)$$

Where k_0, is propagation constant, A_{n1}, B_{n1}, A_{n2}, B_{n2}, A'_{n2}, B'_{n2}, A_{n3} and B_{n3} are amplitude constants.

$$\Gamma_{n1} = \sqrt{k_0^2 - \alpha_n^2 - \beta^2},$$

$$\Gamma_{n2} = \sqrt{k_0^2\varepsilon_{r2} - \alpha_n^2 - \beta^2},$$

$$\Gamma_{n3} = \sqrt{k_0^2\varepsilon_{r3} - \alpha_n^2 - \beta^2},$$

$$\alpha_n = \frac{(2n+1)\pi}{b}, \ \beta = 2\Pi/\text{wavelength}.$$

The boundary conditions at x = h1, (-h2+d) and y= ± b/2 have been incorporated. Using these boundary conditions in eq. (1), the other field components (3) - (8) can be derived.

A. Normal mode parameters

The propagation constants are evaluated by applying the Galerkin's method to the transformed Green's function matrix relating the voltage and electric fields at various boundaries of the structure and solving for the roots of the determinant of the eq.(1).

$$\begin{aligned} &\sum_{k=1}^{\infty} c_k \sum_{n=0}^{\infty} p_n G_{11} L_{2n}^k L_{2n}^m + \sum_{k=1}^{\infty} d_k \sum_{n=0}^{\infty} q_n G_{12} L_{1n}^k L_{2n}^m = 0. \\ &\sum_{k=1}^{\infty} c_k \sum_{n=1}^{\infty} p_n G_{21} L_{2n}^k L_{1n}^m + \sum_{k=1}^{\infty} d_k \sum_{n=1}^{\infty} q_n G_{22} L_{1n}^k L_{1n}^m = 0. \end{aligned} \quad (9)$$

The set of basis functions used in this analysis are sinusoidal and expressed as follows:

$$V_z(y) = \frac{\cos\left[2(n-1)\pi\frac{(y-y_i)}{w_i}\right]}{\sqrt{1-\left[\frac{2(y-y_i)}{w_i}\right]^2}} \quad , \quad V_y(y) = \frac{\sin\left[2n\pi\frac{(y-y_i)}{w_i}\right]}{\sqrt{1-\left[\frac{2(y-y_i)}{w_i}\right]^2}}, \quad (10)$$

Where w_i being the width of the i^{th} fin, y_i is the distance from origin to the center of i^{th} fin.

B. Characteristics impedances

Mode characteristics impedance of the coupled unilateral finlines lines are evaluated for all hybrid modes in a straight forward manner by calculating the power associated with a given finline for a given mode. The finline mode impedance is given by,

$$Z_{lm} = \frac{(V_{lm})^2}{P_{lm}}. \qquad (11)$$

Where V_{lm} is the modal voltage of the l^{th} slot given by the integral of the electric field across the slot and P_{lm} is the partial modal power associated with the same slot when the m^{th} normal mode is excited.

3. FILTER DESIGN APPROACH

The wide band pass filter is designed with three parallel-coupled unilateral finlines approximately quarter wavelength long. In this paper multi resonators are cascaded to achieve high rejections. The six port impedance matrix parameters for a section of three coupled finlines of length l are found from mode characteristic impedances, phase velocities and voltage ratios.

This three-coupled finline structure supports three dominant modes as OE, EE, and OO, which correspond to 1, 2 and 3, respectively. Each mode has its own modal phase constant, eigen voltage vector and characteristic impedance.[7-9] The eigen voltage matrix for symmetrical three line which have equal fin-width and spacing are given by,

$$[M_V] = \begin{bmatrix} 1 & 1 & 1 \\ m_1 & 0 & m_3 \\ 1 & -1 & 1 \end{bmatrix} \qquad (12)$$

Each vector of $[M_V]$ is the eigen voltage vector of the matrix product [L] [C]. The matrix $[M_V]$ can be used to derive the relation between port voltages and port currents.

$$\begin{bmatrix} V_A \\ V_B \end{bmatrix} = \begin{bmatrix} Z_A & Z_B \\ Z_B & Z_A \end{bmatrix} \begin{bmatrix} I_A \\ I_B \end{bmatrix} \qquad (13)$$

Where

$$[V_A] = [V_1, V_2, V_3]^T, [V_B] = [V_4, V_5, V_6]^T,$$

$$[I_A] = [I_1, I_2, I_3]^T, [I_B] = [I_4, I_5, I_6]^T$$

And the impedance matrix $[Z_A]$ and $[Z_B]$ can be derived as

$$\left[Z_A\right] = [M_V]\ \ diag[-jZ_{mi}\cot\theta_i][M_V]^T \tag{14}$$

$$\left[Z_B\right] = [M_V]\ \ diag[-jZ_{mi}\csc\theta_i][M_V]^T \tag{15}$$

Now $\theta_i = \beta_i l$ with β_i is the phase constant of the i^{th} mode, l the length of the coupled section, and Z_{mi} given by

$$Z_{mi} = \frac{Z_{oi}}{m_i^2 + 2} \tag{16}$$

Where Z_{oi} is the characteristic impedance of i^{th} mode.

Eqn. (6), (7), (8) are derived from eqn. (5).

$$m_1 Z_{m1} - m_3 Z_{m3} = JZ_A Z_B \tag{17}$$

$$m_1^2 Z_{m1} - m_3^2 Z_{m3} = Z_A(J^2 Z_A Z_B + 1) \tag{18}$$

$$Z_{m1} + Z_{m3} = Z_B(J^2 Z_A Z_B + 1) \tag{19}$$

After simplifying eqn. (6), (7) & (8) we obtain the below equations

$$m_1 Z_{m1} \approx \left[\frac{2+\mu^2}{2\mu}\right](Z_0/2)(J^2 Z_0^2 + JZ_0 + 1) \tag{20}$$

$$m_3 Z_{m3} \approx \left[\frac{2+\mu^2}{2\mu}\right](Z_0/2)(J^2 Z_0^2 - JZ_0 + 1) \tag{21}$$

where

$$\mu = \frac{\sqrt{2\left[2(Z_{ee}-Z_{oo})^2 - Z_{oe}(Z_{oe}-Z_{ee}-Z_{oo}) - Z_{ee}Z_{oo}\right]}}{2Z_{ee}-Z_{oe}-Z_{oo}}$$

The value of JZ_O for each admittance inverter can be determined from the values of lumped circuit elements of the low pass prototype.[16]

$$J_1 = \frac{1}{Z_0}\sqrt{\frac{\pi\Delta}{2g_1}} \tag{22}$$

$$J_n = \frac{1}{Z_0}\sqrt{\frac{\pi\Delta}{2g_{n-1}g_n}},\ for\ n = 2,3.....N, \tag{23}$$

$$J_{N+1} = \frac{1}{Z_0}\sqrt{\frac{\pi\Delta}{2g_N g_{N+1}}} \tag{24}$$

Where $\Delta = \frac{\omega_2 - \omega_1}{\omega_0}$

For N = 3, the values of g_1 to g_{N+1} are given below.

g_1 = 1.5963, g_2 = 1.0967, g_3 = 1.5963, g_4 = 1.0000.[10] Once JZ_O is known the values of m_1Z_{m1} and m_3Z_{m3} for each coupled section can be known. The values of m_1Z_{m1} and m_3Z_{m3} for section I are 82.02 Ω and 64.69 Ω respectively and for the section II are 37.65 Ω and 40.94 Ω respectively. The designed data from the above is calculated and finally the filter is optimized. This data have been shown in Table 1.

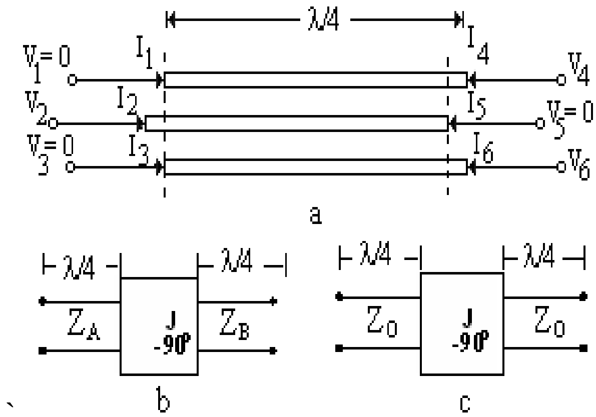


Fig. 2: Reduction of a coupled three-finline section to a two-port network (a) Coupled three-line section as a six-port network (b) Equivalent admittance inverter (c) Further approximated admittance inverter.

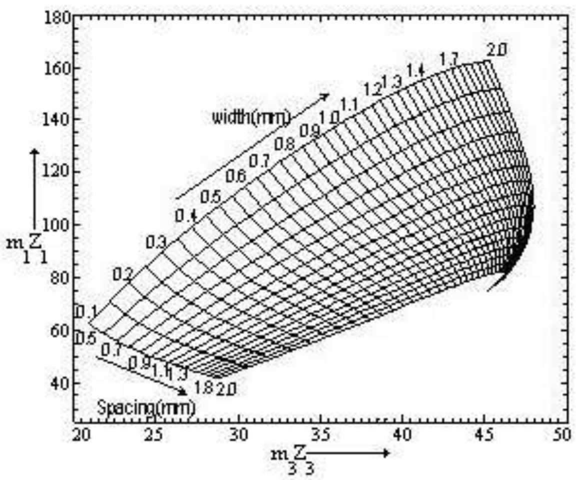


Fig. 3: The bandpass filter design graph for a symmetric three unilateral finline structure. [Substrate dielectric constant εr=2.2, substrate thickness (D) = 0.8 mm, frequency =10 GHz].

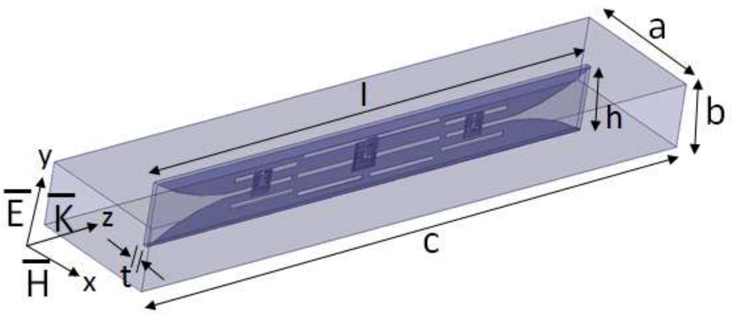
The design graph in Fig. 3 for ε_r=2.2 is used to determine the line width and line spacing of three coupled unilateral finlines at 10 GHz. Due to symmetry of filter only the width, spacing and length of two sections has been mentioned here. The simulated three dimension model of three finline wide bandpass filter structure is shown in Table.1. This parallel arrangement gives relatively large coupling for a given spacing between resonators, and thus this filter structure is particularly convenient for large bandwidths as compared to the other structures.[11]

Table 1: Three finline coupled wide bandpass filter (resonator parameters) dimensions are in mm.

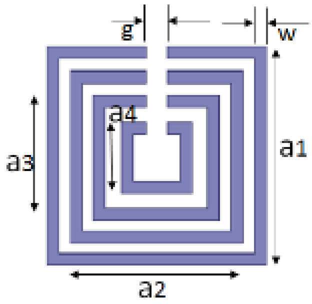
Dimentions	Designed Data		Optimized Data	
	Section 1	Section 2	Section 1	Section 2
W	0.650	0.68	0.750	0.750
S	1.320	2.370	1.400	2.400
L	9.592	10.164	12.970	13.413
G	1.975	2.033	1.076	1.633

4. EFFECTS OF MULTI SPLIT RING RESONATOTRS (SRR)

Now concentric Split Ring Resonator (SRR) concept has been introduced on other side of substrate of this wide band pass filter. These SRRs creates negative effective permeability $\mu_{\mathbf{eff}}$ (ω) at desired frequency. It creates a notch at resonance frequency. The resonance response can be adjusted by varying the geometrical parameters each ring resonators. The notch can be controlled by number of concentric SRRs and their placing. This is the useful characteristics for converting the wideband pass filter in to quad bandpass filters. This is a new technique in finline technology to develop a quad bandpass filters. Split Ring Resonator (SRR) can be seen as a corresponding LC circuit.[12-15] The response this quad bandpass filter is shown in Fig.4.



(a)



(b)

Fig. 4 (a) Simulated structure of parallel coupled three finline wide bandpass filter housed in X-band wave guide (dimensions are, a=22.86mm, b=10.16mm, c=111mm) and RT-Duriod 5880™ dielectric substrate parameters (dielectric constant(εr) =2.2, substrate thickness (t) = 0.8 mm, length (l) = 90 mm, height(h) = 10.16 mm, loss tangent is 0.0009, frequency =10 GHz), (b) Four concentric SRR (dimensions mentioned in Table. 2.

Table 2: Concentric SRR dimensions.

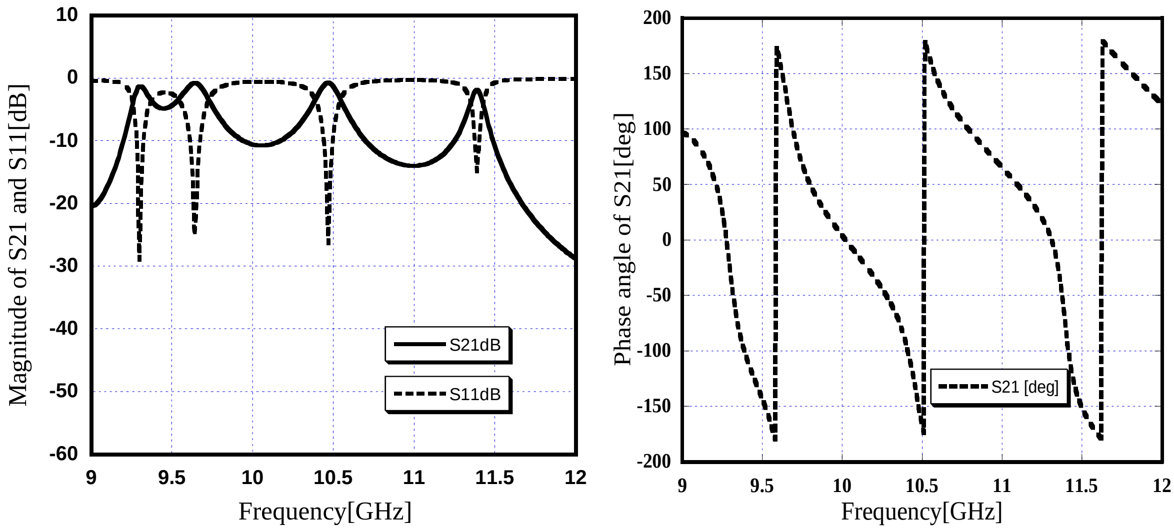
SRR1 Parameters (mm)	SRR 2 Parameters (mm)	SRR 3 Parameters (mm)	SRR 4 Parameters (mm)
a1 = 9.3 w = 0.3 g = 0.3	a2 = 7.3 w = 0.3 g = 0.3	a3 =5.3 w = 0.3 g = 0.3	a4 = 3 w = 0.3 g = 0.3

Some of the important observations are mentioned below.

(1) Large band separation and sharp response is possible with more number of concentric SRR and their placing of the structure.

(2) Again quad bandpass is tradeoff between band separation and return losses.

(3) Here the combinations of three and four concentric SRRs have been used. Four concentric SRRs at center of the structure and three concentric SRRs are used near power launched, power delivered sides of this filter. This extra SRR at the center is useful for S11is less than -15dB.



(a) (b)

Fig. 5: (a) Response of quad-bandpass filters with three coupled finline and concentric multi split ring resonators. (b) Phase angle of S21 and S11.

5. CONCLUSION

Multi-band components are key devices to reduce the size and the cost of a multi-standard wireless system because the overall becomes almost two times smaller compared to the systems implemented using single-band components. That makes multi-band components very attractive for the miniaturization of wireless transceivers. Quad bandpass filters play an important role in the modern transceivers. The most important advantages are, these can be widely used in millimeter wave applications such as automotive, radar and Radio-Frequency Identification (RFID) systems transceivers for portable wireless communication devices. Modern communication transceivers require high performance microwave filters with low insertion loss, high frequency selectivity and small group delay variations. Most of the above said parameters are obtained with this proposed quad bandpass filter with three coupled finlines with concentric multi split ring resonator (metamaterials).

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V. Mahusudana Rao received his B. Tech degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad, India in 2000. He joined as an Engineering Assistant in All India Radio &Doordarshan (PrasarBharati Broadcasting Corporation of India) in 2000. Organization sponsored him for M. Tech studies in I.I.T Kanpur, India in 2006. He received his M. Tech (Microwave and Photonics) degree from Electrical Engineering department of I.I.T Kanpur in 2008. He is pursing PhD in JNTU Kakinada India. Currently he is working in Doordarshan (DD National) Tuni, Under DMC Rajahamahendravaram, Andhrapradesh state, India.

Dr. B. Prabhakara Rao received his B.Tech degree in Electronics and communication Engineering from Sri Venkateswara University, India in 1979 and M. Tech from Sri Venkateswara University, India in 1982. He obtained his P.hD degree from Indian Institute of Science, India in 1995. He is currently working as Director for department of Nano technologies of Jawaharlal Nehru Technological University Kakinada, India and earlier he was Rector, and In-charge Vice-Chancellor this University. He has been coordinator for several all India Council for technical education projects. He published several papers in national journals, international journals and presented papers at conferences. His areas of interest include optical communications, Microwave Engineering, satellite communications, cellular and mobile communications. He is Fellow of IETE and IE (I). He is life member of ISTE.