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RESEARCH ARTICLE

Influence of optical filtering on transmission capacity in single mode fiber communications

M. Venkata SUDHAKAR (✉)[1], Y. Mallikarjuna REDDY[2], B. Prabhakara RAO[1]

1 Department of Electronics and Communication Engineering, Jawaharlal Nehru Technological (JNT) University, Kakinada, AP, India
2 Department of Electronics and Communication Engineering, Vasireddy Venkatadri Institute of Technology, Guntur, AP, India

Abstract This paper presents the design and analysis of optical filters that are placed at the output of directly modulated vertical cavity surface emitting laser (VCSEL) in the process of inexpensive transmitter's implementation for upcoming generation optical access network. Generation of non return to zero (NRZ) optical signal from the transmitter for 110 km error-free single mode fiber (SMF) transmission at 10 Gb/s with bit error rate (BER) of 10^{-30} in the absence of the external modulator and encoder was proposed. Effects of super-Gaussian and Butterworth optical filters at VCSEL output were demonstrated to maximize performance of SMF optical systems without need of any dispersion compensation technique.

Keywords single mode fiber (SMF), optical filter, dispersion, data rate

1 Introduction

Single mode fibers (SMFs) are best suited for long reach optical communication (OC) to establish high data rate broad-band connectivity service networks used for video conference, tele-medicine, e-banking and e-learning. Vertical cavity surface emitting laser (VCSEL) offers several advantages like large coupling efficiency [1], existing in a transmitter optical sub-assembly (TOSA) [2], reliability [3], single mode operation and smaller threshold current [4]. The employment of VCSEL as an alternative to edge emitting laser is extremely advantageous because of their built in strengths like excellent beam quality and decreased production cost [5]. The benefits of VCSEL over distributed Bragg reflector (DBR) and distributed feedback (DFB) laser are small in utilization of power and reduced cost due to its compactness attractive for optical telephone networks [6]. Therefore, VCSEL is the good choice for implementing low cost internet based services.

In the absence of dispersion compensation schemes, Mach-Zehnder (MZ) and electro-absorption (EA) modulators based transmitter's transmission length is restricted to 80 km of SMF at 10 Gb/s [7–9]. EA and MZ modulators based transmitters have larger consumption of power, larger size and high cost in comparison with transmitters employing directly modulated VCSEL.

The transport of chirped pulses from VCSEL through the SMF is highly influenced by chromatic dispersion (CD) of SMF. Dispersion is the significant source for inter symbol interference (ISI). The VCSEL chirp is the principal component that restricts transmitting distance to 10 km at 10 Gb/s in SMF at 1550 nm [10,11].

In VCSEL based optical-systems, various methods have been proposed to reduce the dispersion effects in SMF, such as dispersion compensation fiber [12], equalization at the receiver [13], inversion dispersion fiber (IDF) [14] and injection locking [15]. These schemes either add excessive power consumption with an increase in the complexity of the system or enhance the size and cost of the optical system.

We proposed a new approach with the data transfer rate at 10 Gb/s in access networks. The VCSEL based proposed system comprises of optical filter and pulse generator along with VCSEL in transmitter. This type of proposed work is presented in developing transmitter with the optical filtration scheme. This paper is organized as follows: The description of the method adopted is presented in Section 2. Results are discussed and compared with research work done earlier in Section 3. Subsequently, the conclusions are presented in Section 4.

2 Theories

The optical filtering method at the transmitter is illustrated

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E-mail: venkatasudhakarm@gmail.com

in Fig. 1. Optical transmitter consists of three parts: pulse generator, VCSEL and optical band pass filter (OBPF). 10 Gb/s pseudo random bit sequence (PRBS) non return to zero (NRZ) signal is generated by the pulse generator to drive the VCSEL.

The working of directly modulated VCSEL is highly influenced by frequency characteristics of laser chirp. The equation for the chirp in terms of laser optical output power $P(t)$ is expressed as [16,17]

$$\Delta v(t) = -\frac{\alpha}{4\pi}\left[\frac{\mathrm{d}}{\mathrm{d}t}\Big(\ln P(t)\Big) + kP(t)\right], \tag{1}$$

where $\Delta v(t)$ is the laser chirp, k is the coefficient of adiabatic chirp and α is the line width enhancement factor. According to Eq. (1), the first term determines transient chirp which does not depend on structure of laser, and the latter term corresponds to geometry dependent adiabatic chirp. The adiabatic chirp coefficient is given by

$$k = \frac{2\Gamma\varepsilon}{hv\eta V_{\mathrm{a}}}, \tag{2}$$

where Γ is the mode confinement factor, η is the quantum efficiency, h is the plank's constant, v is the optical frequency, V_{a} is the active layer volume, and ε is the compression factor of nonlinear gain. The VCSEL chirp usually increases the pulse width of the signal after travelling through the fiber and decrease the performance of the optical system due to the combined effect of the laser chirp and fiber dispersion [18]. The laser output power is given by

$$P(t) = \frac{V_{\mathrm{a}}S(t)\eta hv}{2\Gamma\tau_{\mathrm{p}}}, \tag{3}$$

where τ_{p} is the life time of the photon. The laser rate equations for the carrier density $N(t)$, photon density $S(t)$ and optical phase $\phi(t)$ are given by [19,20]

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \frac{\eta_{\mathrm{i}}\Big(I(t)-I_{\mathrm{off}}(T)\Big)}{qV_{\mathrm{a}}} - \frac{g_0\Big(N(t)-N_0\Big)S(t)}{1+\varepsilon S(t)} - \frac{N(t)}{\tau_{\mathrm{c}}}, \tag{4}$$

$$\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = \frac{1}{2}\alpha\left\{\Gamma g_0\Big(N(t)-N_0\Big) - \frac{1}{\tau_{\mathrm{p}}}\right\}, \tag{5}$$

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = -\frac{S(t)}{\tau_{\mathrm{p}}} + \frac{\Gamma\beta N(t)}{\tau_{\mathrm{c}}} + \frac{\Gamma g_0\Big(N(t)-N_0\Big)S(t)}{1+\varepsilon S(t)}, \tag{6}$$

where η_{i} is the injection efficiency, $I_{\mathrm{off}}(T)$ is the thermal offset current, $I(t)$ is the injection current, τ_{c} is the carrier life time, β is the fraction of spontaneous emission coupled into the lasing mode, N_0 is the carrier density at transparency, q is the charge of electron and g_0 is the differential gain coefficient.

The super-Gaussian and Butterworth OBPF's are utilized for tailoring of light at the VCSEL output. VCSEL operating wavelength is lined-up around the transmitting edge of OBPF. The desired optical filtering of chirped signal coming from VCSEL is the fundamental to dispersion mitigation and it is accomplished by changing the bias, driving voltage, laser and OBPF parameters. The transfer function of the Gaussian OBPF is given by

$$T_{\mathrm{g}}(f) = \exp\left(-\ln(x)\left(\frac{2(f-f_{\mathrm{c}})}{\Delta f_{3\ \mathrm{dB}}}\right)^{2N}\right), \tag{7}$$

where $x = 2$ corresponding to super Gaussian filter [21], $T_{\mathrm{g}}(f)$ is the Gaussian OBPF transfer function, $\Delta f_{3\ \mathrm{dB}}$ is filter 3 dB bandwidth, f is the frequency, N is filter order and f_{c} is the central-frequency of filter. The transmittance of Butterworth OBPF is defined as [22,23]

$$|H_{\mathrm{b}}(f)|^2 = \frac{1}{1+\left(\frac{2(f-f_{\mathrm{c}})}{\Delta f_{3\ \mathrm{dB}}}\right)^{2N}}, \tag{8}$$

where $H_{\mathrm{b}}(f)$ is the Butterworth OBPF transfer function. Standard SMF is employed for signal transmission in between transmitter and receiver. The receiver consists of four parts: variable optical attenuator (VOA), avalanche photo-diode (APD), Gaussian low-pass filter (LPF) and bit error rate (BER) analyzer. VOA between SMF and APD is used for receiver sensitivity and BER measurements. APD is used for optical conversion of the electrical signal; APD noise is alleviated by utilizing the Gaussian LPF with transmittance $H_{\mathrm{g}}(f)$ of

$$H_{\mathrm{g}}(f) = \exp\left(-\ln(\sqrt{2})\left(\frac{f}{f_{\mathrm{g}}}\right)^{2N}\right), \tag{9}$$

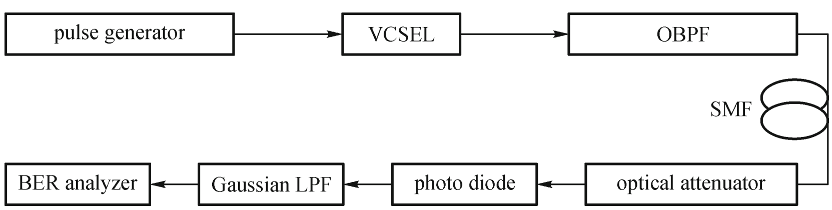


Fig. 1 Optical filtering at the transmitter. VCSEL: vertical cavity surface emitting laser; OBPF: optical band pass filter; SMF: single mode fiber; LPF: low-pass filter; BER: bit error rate

where f_g is the cut-off frequency of LPF. Butterworth and Gaussian filters are mathematically easier to formulate and are used primarily because they are simple to synthesize for practical optical system designs.

3 Results and discussion

We examined the effect of an OBPF at the VCSEL output and analyzed its influence on performance of the SMF link using practical commercial OC system design and Matlab software's. 10 Gb/s PRBS NRZ transmission signal having a length of $2^{23}-1$ was generated by pulse generator with peak-to-peak voltage (V_{pp}) of 0.55 V. The VCSEL model was used in computations with the following parameters: quantum efficiency = 0.4, volume of active layer = 80 e^{-12} cm^3, injection efficiency = 1, photon life time = 8 ps, carrier life time = 2 ns, carrier density at transparency = 1 e^{17} cm^{-3}, differential gain coefficient = 1.0 e^{-15} cm^2, gain compression coefficient = 8 e^{-17} cm^3, line width enhancement factor = 3.2, spontaneous emission factor = 1 e^{-6}, mode confinement factor = 0.9, bias current = 9.62 mA, modulation current = 8 mA and wavelength = 1550.127 nm.

Adiabatic chirp of 5 GHz and 2.1 dB extinction ratio (ER) were developed at the laser output. The second-order super Gaussian and third-order Butterworth OBPF's were running at 193.414 THz central frequency. The bandwidths of super-Gaussian and Butterworth OBPF's were 10 and 7.8 GHz respectively.

The results were attained for a SMF with the following parameters: length = 110 km, CD = 16.75 ps/nm/km, effective core area = 80 μm^2, wavelength = 1550 nm, attenuation = 0.2 dB/km, nonlinear refractive index = 2.6 e^{-20} m^2/W and slope of dispersion = 0.075 ps/nm^2/km. APD responsivity and dark current were considered to be 1 A/W and 10 nA respectively. Gaussian LPF cut off frequency was placed at 10 GHz and N was 1.

The chirp and power at VCSEL output are depicted in Fig. 2(a), the rising edge of transient chirped signal is going with higher speed when compared with falling edge of transient chirped signal. This results in broadening of the transmitted pulses and restricts the reach of SMF link.

From Fig. 2(b), it is clear that the super-Gaussian OBPF converts adiabatic chirped signal to flat-top chirped signal over the mark bit period and produces rapid spikes over the space bit period; this results in π phase shift for the period of "0" bit and also it eliminates the transient chirp along with modification of the power signal, in addition to that the ER value increased to 11.76 dB by frequency modulation (FM) to amplitude modulation (AM) transformation. The author successfully analyzed the effects of Butterworth filter on the tailoring of the VCSEL output so that the result is almost same as super-Gaussian OBPF output.

The performance of the link with PRBS input data was compared between the proposed method and lithium niobate ($LiNbO_3$) based transmitter. Pulse generator, continuous-wave (CW) laser and dual-drive $LiNbO_3$ modulator [24] are parts of $LiNbO_3$ transmitter scheme. $LiNbO_3$ based scheme was used in computations with the following parameters: switching bias-voltage = 4 V, radio frequency (RF) switching voltage = 4 V, bias-voltage 1 = 0 V, bias-voltage2 = 2 V, modulation voltage1 = 2 V and modulation voltage 2 = −2 V. CW laser was operating at the wavelength of 1550 nm.

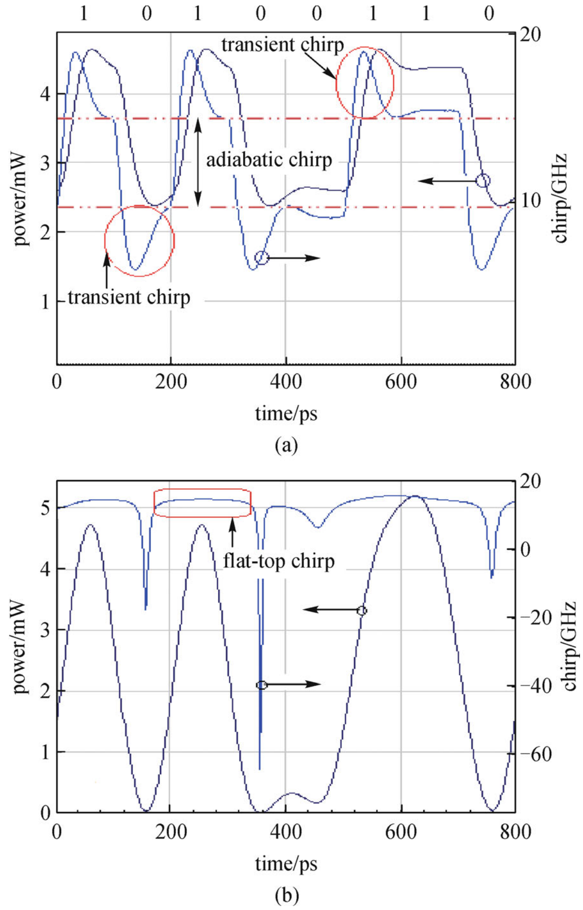
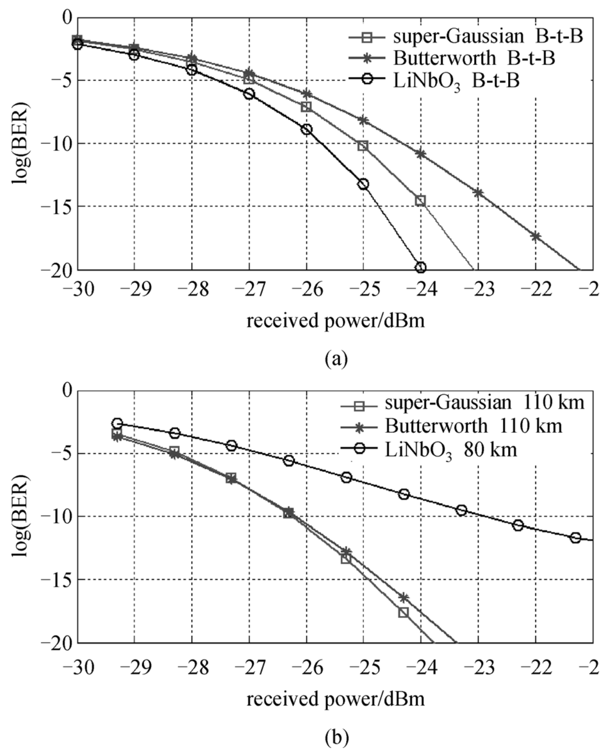


Fig. 2 Waveforms of optical filtering scheme. (a) VCSEL output and (b) super-Gaussian OBPF output for 10100110 bit sequence

The back-to-back (B-t-B) optical receiver sensitivities were measured at BER of 10^{-9} for $LiNbO_3$ and proposed-scheme. Sensitivities of $LiNbO_3$, super-Gaussian and Butterworth are −26, −25.3 and −24.7 dBm respectively as shown in Fig. 3(a), the 0.7 dBm penalty for super-Gaussian and 1.3 dBm penalty for Butterworth are due to the restricted bandwidth of OBPF and VCSEL.

The optical receiver sensitivities were measured at BER of 10^{-9} for $LiNbO_3$ based method at 80 km, proposed scheme with super-Gaussian and Butter-worth at 110 km and their sensitivities are −23.7, −26.5 and −26.5 dBm respectively as shown in Fig. 3(b), the 2.8 dBm sensitivity improved in the proposed-method is due to the filtering effect.



(a)

(b)

Fig. 3 BER performance comparison. (a) Measured at back-to-back (B-t-B) and (b) measured with $LiNbO_3$ at 80 km and proposed scheme at 110 km

Figure 4 illustrates the BER performance for various lengths of SMF with $LiNbO_3$ based transmitter and the proposed method, BER value for $LiNbO_3$ after 84.5 km of SMF is greater than 10^{-9}, the BER value with super-Gaussian and Butterworth OBPF is less than 10^{-9} at 110 km of SMF.

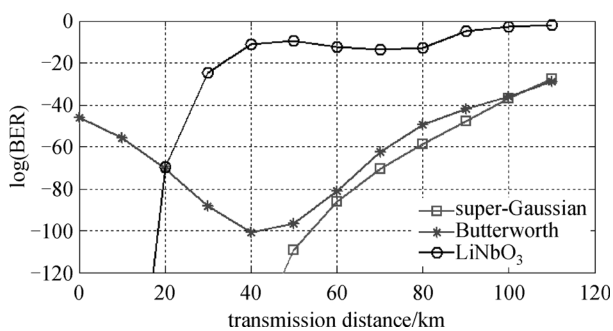


Fig. 4 BER values for different lengths of SMF

The capabilities of dispersion control of proposed method after 110 km and $LiNbO_3$ based signal after 80 km are shown in Fig. 5. At the BER of 10^{-9}, the $LiNbO_3$ scheme is able to tolerate nearly ±18 ps/nm CD. Nonetheless, the proposed method (super-Gaussian) shows distinct CD tolerance; the positive value is closed to 26.7 ps/nm and negative value is around −12.8 ps/nm. With application of Butterworth filter the achieved CD tolerance is between −15.5 and 28.5 ps/nm. It is clearly visible that CD tolerance is higher with this proposed method compared to $LiNbO_3$ based method.

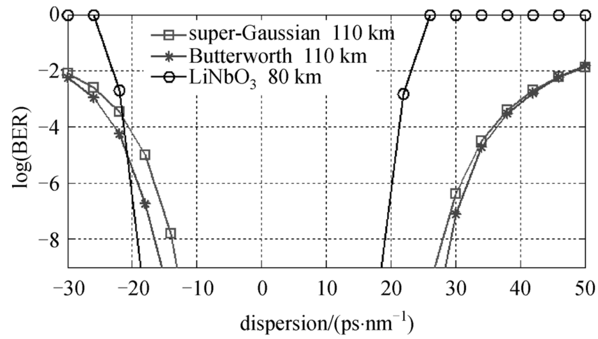


Fig. 5 Dispersion tolerance of $LiNbO_3$ and proposed scheme

Figure 6 exhibits the calculated BER performance for different data rates. After propagation over 110 km of SMF, the BER value for proposed method is changed from 10^{-27} to 10^{-9} when the data rate raised from 7 to 12.3 Gb/s. The BER value of $LiNbO_3$ scheme is greater than 10^{-9} after 80 km with 10.6 Gb/s bit rate.

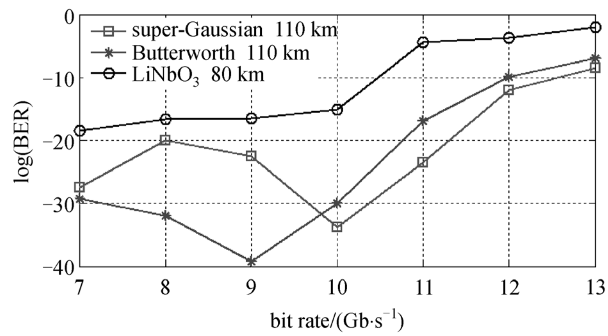


Fig. 6 BER and Bit rate relationship

The eye-patterns are employed to examine the ISI. The width of the eye-opening describes the time period in which received signal is sampled without error as result of ISI. The simulated eye-diagrams after the receiver are presented for $LiNbO_3$ and proposed system at 10 Gb/s bit rate. The proposed optical filtering scheme is used to enhance the signal quality by the alteration of the chirp and extinction ratio of the optical signal at VCSEL output, this results much clearer eye-diagrams after 110 km transmission. Eye diagram of $LiNbO_3$ scheme is presented in Fig. 7(a). Eye-patterns of the proposed transmitters with super-Gaussian and Butterworth filter are shown in Figs. 7(b) and 7(c) respectively. Eye-opening factors of $LiNbO_3$, super-Gaussian and Butterworth are 0.7, 0.917 and 0.912 respectively. Eye-opening is higher after 110 km of SMF transmission with the proposed scheme compared

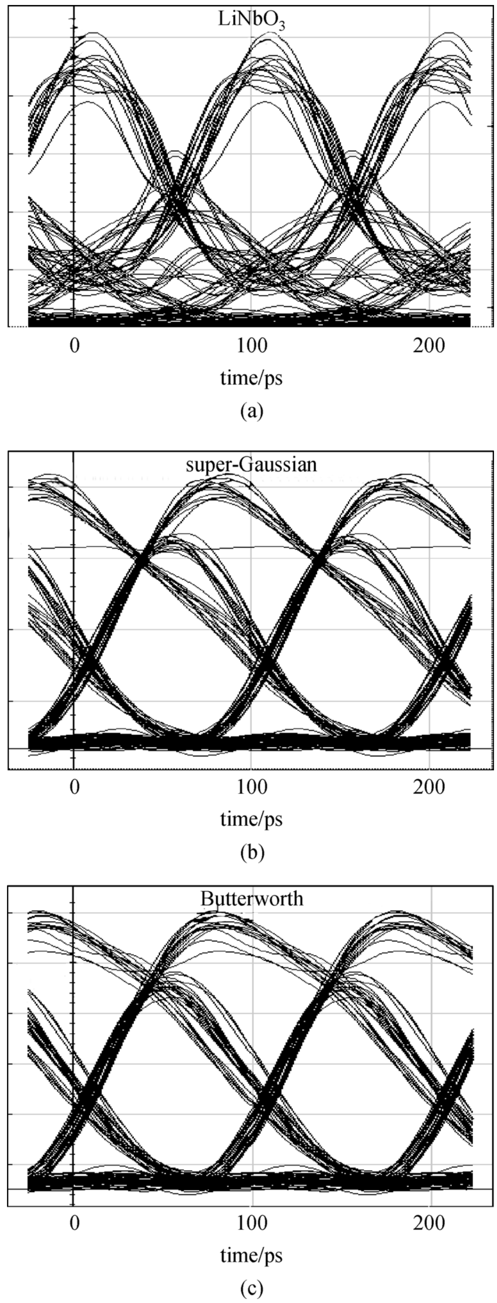


Fig. 7 Eye-patterns after 110 km of SMF. (a) $LiNbO_3$; (b) super-Gaussian; (c) Butterworth

with $LiNbO_3$ based transmitter.

The important features of proposed-method from their early schemes are summarized in Table 1. The current approach has greater data rate of 10 Gb/s, large transmission distance and better sensitivity in comparison with preceding methods.

4 Conclusions

The transmission performance of the system in terms of the eye diagram and BER was discussed. The obtained results substantiate that super-Gaussian and Butterworth filters at the VCSEL output raise the transmitting capability of the optical system in comparison with $LiNbO_3$ and VCSEL based previous schemes. The special feature of this scheme is the cost effective telecom signal transmission. Therefore, the method adopted is simple and provides best performance in the emerging access networks.

Table 1 Comparison of current work with preceding methods

parameter	proposed	VCSEL [10]	IDF [14]
bit rate	10 Gb/s	10 Gb/s	4.25 Gb/s
fiber length	110 km	10 km	45.4 km
sensitivity	– 26.5 dBm	– 17.88 dBm	– 24.5 dBm
wavelength	1550 nm	1550 nm	1550 nm
laser type	VCSEL	VCSEL	VCSEL
fiber type	SMF	SMF	SMF and IDF

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M. Venkata Sudhakar was born in 1980. He received B.Tech Degree in Electronics & Communication from Andhra University in 2002 and M.Tech Degree in Computer & Communication from B.I.H.E.R in 2005. He is working towards Ph.D in Electronics & Communications Engineering from Jawaharlal Nehru Technological University, Kakinada. His current research focus on signal processing and optical communications. He published more than 10 technical papers in national and international journals and conferences.

Y. Mallikarjuna Reddy is principal and professor in the Department of Electronics and Communication Engineering (ECE) at Vasireddy Venkatadri Institute of Technology (VVIT), Nambur, Guntur, AP. He has 23 years of teaching experience. He obtained his B.E (ECE) from Osmania University, Hyderabad, India in 1987, M.Tech (Instrumentation & Control Systems) from Jawaharlal Nehru Technological University (JNTU), Kakinada, India in 1990, and Ph.D (ECE) from Osmania University, Hyderabad, India in May 2009. He worked as teaching faculty at RVR & JC College of Engineering, Guntur, A.P, India, from 1990–2001. He was a professor and head, Department of ECE, at various Engineering Colleges during 2000- 2007. He did Ph.D in the field of radar signal processing and neural networks at Osmania University under the guidance of Dr. S. Vathsal, scientist-G, Director, ER & IPR directorate, DRDO, New Delhi. He is a member of the IE(I) and ISTE, India. He has guided many B.Tech and M.Tech projects. He has published three paper in national journals, 18 papers in international journals and 16 papers in international conferences. He is author of "Probability Theory and Stochastic Process", Fourth edition, Published by Universities Press (India) Private Limited 2013, Hyderabad.

B. Prabhakara Rao obtained B.Tech. and M.Tech from S.V. University, Tirupathi with Specializations in Electronics & Communications Engineering, Electronic Instrumentation & Communications Systems in the years 1979 and 1981 respectively. He received the Doctoral degree from Indian Institute of Science, Bangalore in the area of Sonar signal processing in the year 1995. He has more than 31 years of experience in teaching and research. He held different positions in his career, as Head of the Department and Vice Principal, Director (Institute of Science and Technology), Director of Evaluation, Director of Foreign Universities Relations, Director –Admissions during in the years 2001 to 2013. Presently he is working as Rector and Director-Admissions (Additional Charge) from July 2013 in Jawaharlal Nehru Technological (JNT) University, Kakinada. He completed 2 AICTE Projects for 8.0 Lakhs each in the areas of satellite communications and communications. He guided 12 Ph.D candidates and presently guiding 18 Ph.D scholars. He has published more than 180 technical papers in national and international journals and conferences. He is Senior IEEE (USA) member, Fellow of the Institution of Engineers (Kolkatta), Fellow of Institution of Electronics & Telecommunication Engineers, Life Member of Indian Society of Technical Education, Life Member of Society of Electromagnetic Interference/Electromagnetic Compatibility (EMC) Association, Life Member of Indian Science Congress Association(Kolkatta).