Transmission of 112 Gb/s dual carrier PolMux DQPSK system

HARMANPREET KAUR SANDHU, R. S. KALER*
Electronics & Communication Department, Thapar University, Patiala, India

In this paper, the multilevel modulation format, Polarization multiplexed differential quadrature phase-shift keying has been investigated by means of numerical simulations. The performance of transmission of 112 Gb/s dual carrier PolMux NRZ-DQPSK is compared with that of dual carrier PolMux RZ-DQPSK systems over 20 km of standard single mode fiber with respect to changes in state of polarization. It is observed that PolMux NRZ-DQPSK systems gives an improvement of 1.25 dB in OSNR for BER is 10^{-3} than PolMux RZ-DQPSK system and the frequency spectrum of PolMux NRZ-DQPSK signal is much narrower than PolMux RZ-DQPSK signal at the receiver side. Also, proposed PolMux NRZ-DQPSK system gives better results for compensation of chromatic dispersion and enhanced equalization phase noise than PolMux RZ-DQPSK communication system.

(Received October 16, 2016; accepted August 9, 2017)

Keywords: Multi-level modulation formats, Polarization multiplexing, Differential quadrature shift keying (DQPSK), Optical fiber polarization, Polarization mode dispersion (PMD)

1. Introduction

Nowadays, there is a need for more bandwidth efficient modulation formats to transmit high data rates in more densely spaced wavelength division multiplexed (WDM) systems. Up until a few years ago, optical communication systems primarily employed binary modulation formats for modulating the information on the optical carrier. But they cannot perform in 100G transmission systems due to limited opto-electronics bandwidth and optical signal to noise ratio (OSNR). It restricted the theoretically achievable spectral efficiency to 1 b/s/Hz [1], assuming no overhead is required for forward error correction (FEC).

A further increase in spectral efficiency of WDM systems requires the use of multi-level modulation formats, using either modulation in the amplitude, phase or polarization domain. Among different possible approaches, Polarization multiplexing (POLMUX) together with the differential quadrature phase-shift keying (DQPSK) format is viewed as a promising modulation format for 100 Gb/s transmission links because of its narrow spectral width and robust tolerance to system impairments. Though polarization multiplexing may pose some problems with polarization mode dispersion (PMD), its PMD tolerance is much more than 100 Gb/s on-off-keyed (OOK) signals [2].

A novel method is proposed by C. Porzi et al. [3] for signal processing of multi-level modulation formats such as single-channel single-polarization, dual-channel (DC) single-polarization, and DC PolMux 28 GBaud quadrature phase shift key-modulated signals, which are suitable for 100 G multi-channel coherent systems. An error rate below 10^{-3} has been reported, prior to FEC for all these signals by using digital signal processing (DSP) at the receiver side.

Stefan Wabnitz [4] investigated the performance of 112 Gb/s transmission of both single channel and hybrid WDM PolMux QPSK system with coherent receivers in the presence of fiber non-linearity and PMD, without in-line dispersion management. The distribution of errors and the associated outage probability is numerically estimated by the Importance Sampling technique, in the presence of fiber non-linearity and PMD.

In this paper, the transmission of dual carrier PolMux DQPSK at 112 Gb/s is studied by means of numerical simulations. In particular, a comparison is made between NRZ PolMux DQPSK and RZ PolMux DQPSK systems in terms of tolerance to variations in degree of polarization which affect the Bit error rate (BER) of the system. In section 2, we describe the multi-level modulation format, PolMux DQPSK along with the methods used to mitigate linear impairments like Chromatic Dispersion(CD) and laser phase noise. Section 3 describes in detail the simulation set-up for the transmission of 112 Gb/s Dual carrier PolMux DQPSK over 20 km of standard single mode fiber (SSMF). Section 4 and section 5 contains the results and conclusion respectively.

2. Theoretical analysis

2.1. PolMux DQPSK modulation format

A very narrow optical spectrum and long symbol period, compared to binary modulation formats, can be obtained by combining the two approaches towards multi-level modulation, that is, PolMux and DQPSK, resulting in 4-bits/symbol modulation. In PolMux, independent information in each of the two orthogonal polarizations is transmitted which doubles the spectral efficiency [5]. But the main drawback of PolMux is that it requires polarization sensitive detection due to random birefringence in optical fibers. However, the polarization mode dispersion (PMD) tolerance of PO PolMux LMUX signals is still more than that of binary modulation formats [6], [7]. So PO PolMux LMUX when combined with DQPSK gives promising transmission results while maintaining sound filtering tolerances along with high robustness against chromatic dispersion and PMD with respect to binary modulation formats. In [8], the feasibility of transmission with a 2.5 b/s/Hz spectral efficiency using PolMux -RZ-DQPSK is investigated.

2.2. Degree of Polarization (DOP)

DOP is one of the PMD monitoring technique, and it can be expressed as [9]

$$\mathrm{DOP} = \frac{\left|\int_{-\infty}^{\infty} \mathrm{S}(\omega)\mathrm{S}_0(\omega)\mathrm{d}\omega\right|}{\int_{-\infty}^{\infty} \mathrm{S}_0(\omega)\mathrm{d}\omega}$$

where $\mathrm{S}(\omega)$ is the Stokes vector and $\mathrm{S}_0(\omega)$ is the optical power which is a measurement of the average SOP over the modulation bandwidth, weighted by the power spectrum. The above equation can be solved to express PMD-induced penalty as a function of DOP for the first-order PMD model

$$\varepsilon_{DB}(\mathrm{DOP}) = \frac{A}{(\alpha T)^2}(1 - DOP^2)$$

where A is the system specific constant that depends on the transmit tter and receiver characteristics.

2.3. Least Mean square (LMS) adaptive Filters for Chromatic Dispersion(CD) compensation

LMS filters belong to the class of adaptive filters which models the relationship between input and output signals of a filter in an iterative manner. The Weiner filters can be realized by LMS algorithm. A minimum mean square error is obtained by applying successive corrections to tap-weight vector of the transversal filter in the negative direction of the gradient vector [10]. The N-tap transversal filter is shown in the Fig. 1.

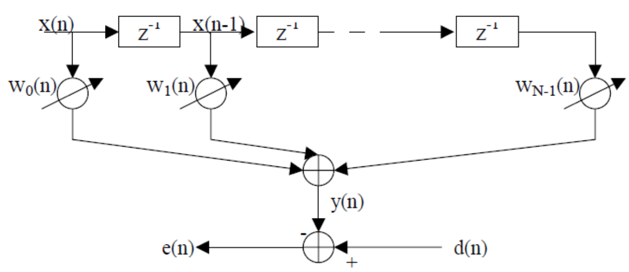


Fig. 1. N-tap transversal filter

The principle of LMS algorithm is given by following operations:

(a) Filtering: $y(n) = \vec{w}^H(n).\vec{x}(n)$
(b) Error estimation: $e(n) = d(n) - y(n)$
(c) Tap-weight vector adaptation:
$$\vec{w}(n+1) = \vec{w}(n) + \mu\vec{x}(n)e^*(n)$$

where 'n' is the number of samples, $\vec{x}(n)$ is the received signal vector, $y(n)$ is the equalized output signal, $\vec{w}(n)$ is the tap-weight vector, $\vec{w}^H(n)$ is the Hermition transform of the tap-weight vector, $d(n)$ is the desired signal, $e(n)$ is the estimated error signal between the desired and output signal, and μ is the step size. The tap-weight vector is updated iteratively until it converges, when the error signal approaches to zero.

2.4. Phase noise analysis

The transmitted signal by the laser contains phase noise which is passed through the transmission fiber and the DSP module that provides CD equalization and thus the phase noise at the transmitter side is close to zero. But the phase noise from the local oscillator (LO) passes only through the CD equalization module which experiences heavy dispersion without dispersion compensating filbers(DCFs) in the transmission system and gives rise to enhanced equalization phase noise(EEPN). Thus, the performance of coherent receivers with digital post equalization of CD is affected by the LO phase noise and so it is important to discuss the impact of total phase noise in the communication system. Tianhua Xu et al. [11] gave a modified correlation between the intrinsic LO laser phase noise and EEPN where total phase noise variance 'σ^2' in the coherent optical communication system is defined as:

$$\sigma^2 = \sigma_{TX}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2 + 2\rho.\sigma_{LO}.\sigma_{EEPN}$$

where ρ is the correlation coefficient between an intrinsic LO phase noise and EEPN, and $|\rho| \leq 1$.

3. Simulation description

The simulation set-up of 112 Gb/s dual carrier PolMux NRZ-DQPSK system is shown in Fig. 2. At the transmitter side, a continuous wave (CW) optical at 193.12 THz is fed to the Mach Zehnder (MZ) Modulator which converts the single carrier into two subcarrier signals with spacing of 28 GHz. It is followed by a delayed Mach-Zehnder Interferometer (MZI) with free spectral range (FSR) of 60 GHz to split the two carriers. Then these carriers are individually passed through polarization beam splitters (PBS) to split them into orthogonal polarizations. These polarized beams are connected to four DQPSK modulators, followed by two multiplexers (MUX) for x and y polarized beams respectively. They are combined by polarization beam combiner and sent through SSMF having CD coefficient of 16 ps/nm/Km over 20 km after amplification.

After fiber transmission, the polarization tracker is used to adjust the SOP to separate the two polarization channel. At the receiver side, PBS is used to split the signal into both orthogonal polarizations again. We can analyse the performance of PolMux NRZ-DQPSK and PolMux RZ-DQPSK systems by creating mismatch in polarizations by changing the device angle of PBS. The polarized signals are passed to two MZI- based filters with 60 GHz FSR before coherent DQPSK demodulation and noise bins are used in the simulation to accommodate the LO phase noise. The detected signals are sent to the Digital Signal Processing(DSP) module where CD is compensated using LMS adaptive filter with appropriate number of taps and normalised LMS(NLMS) is used to compensate EEPN. The effect of PMD is not compensated in the proposed communication system.

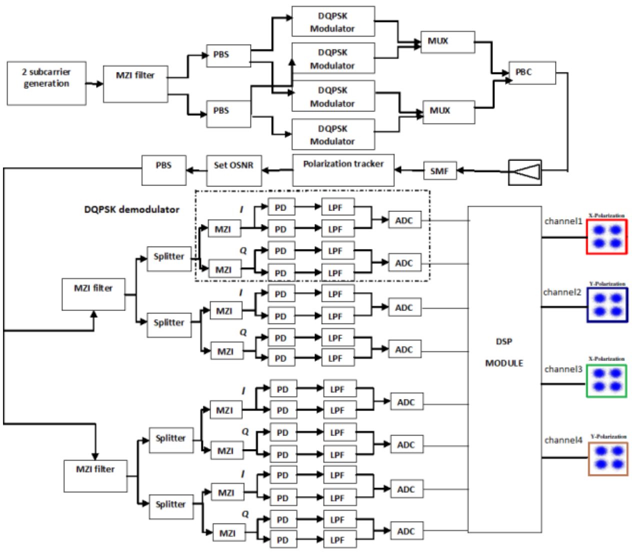


Fig. 2. Simulation diagram of dual carrier PolMux-DQPSK system

4. Results

We have analysed, by means of numerical simulations, the performance of transmission of 112 Gb/s dual carrier PolMux RZ-DQPSK and dual carrier PolMux NRZ-DQPSK systems for SSMF over 20 km having CD coefficient of 16 ps/nm/Km.

4.1. Effect of polarization

In order to investigate the polarization effects, CD and phase noise impacts are not considered and so parameterized inputs are taken at the receiver side. Fig. 3 depicts the performance of dual carrier PolMux RZ-DQPSK and dual carrier PolMux NRZ-DQPSK systems at a device angle of 0^0. The four floors of BER represent the four channels of the two subcarriers where channel 1 and channel 2 are X-polarized and Y-polarized signals of first carrier, and channel 3 and channel 4 are X-polarized and Y-polarized signals of second carrier. The carriers are separated by a FSR of 60 GHz. When channel 1 of both PolMux RZ-DQPSK and PolMux NRZ-DQPSK systems are compared, it is observed that the BER performance of PolMux RZ-DQPSK system is poor than that of PolMux NRZ-DQPSK system as the curve for the former system is less sharp than the latter. For BER=10^{-3} at device angle of 0^0, Optical Signal to Noise Ratio (OSNR) required for PolMux RZ-DQPSK system is 21.25 dB whereas for PolMux NRZ-DQPSK system, it is 22.5 dB. Therefore, PolMux NRZ-DQPSK systems gives an improvement of 1.25 dB in OSNR for BER=10^{-3} than PolMux RZ-DQPSK system.

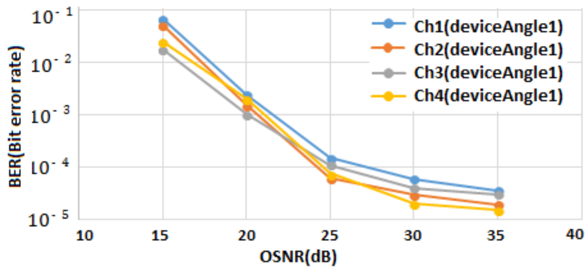


Fig. 3(a). BER vs. OSNR for device angle 0^0 of Dual carrier PolMux RZ-DQPSK

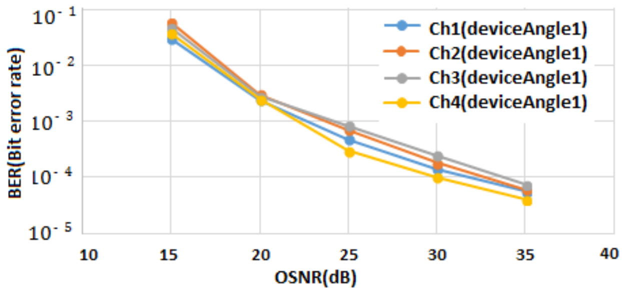


Fig. 3(b). BER vs. OSNR for device angle 0^0 of Dual carrier PolMux NRZ-DQPSK system

The device angle of PBS is varied from 0^0 to 10^0 and Fig. 4 shows the plot of BER vs OSNR of four channels at device angles of 0^0, 5^0, and 10^0 respectively. Here it is seen that when the device angle is increased from 0^0 to 10^0, BER increases sharply from 0.05 to 0.071 in case of dual carrier PolMux RZ-DQPSK and from 0.046 to 0.068 for of dual carrier PolMux NRZ-DQPSK. So when the polarization mismatch increases, the BER performance continues to degrade for both the systems because of PMD-related impairments. But the effects of polarization mismatch are more pronounced in the channels of PolMux RZ-DQPSK than in PolMux NRZ-DQPSK system.

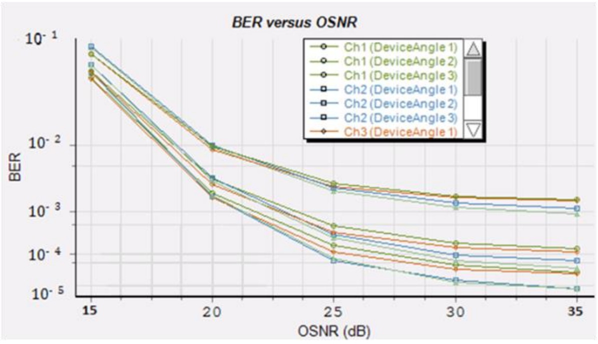


Fig. 4(a). BER vs. OSNR for various device angles of Dual carrier PolMux RZ-DQPSK

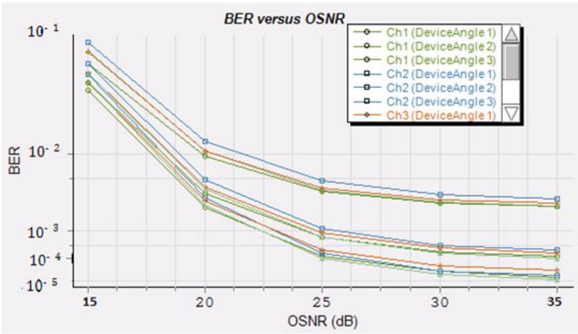
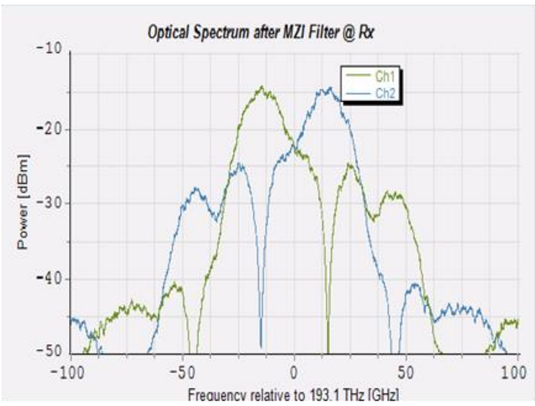
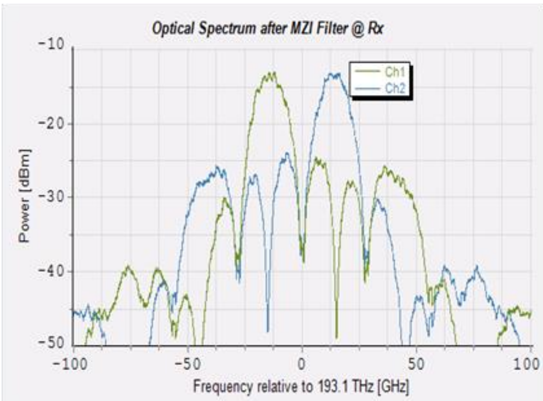


Fig. 4(b). BER vs. OSNR for various device angles of Dual carrier PolMux NRZ-DQPSK



a



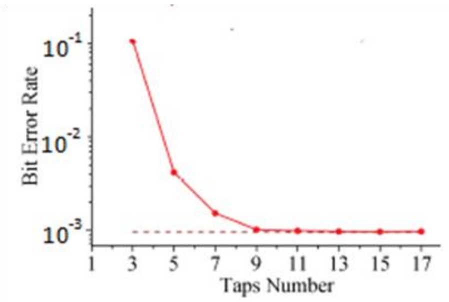
b

Fig. 5. Optical spectrum of (a) Dual carrier PolMux RZ-DQPSK (b) Dual carrier PolMux NRZ-DQPSK system

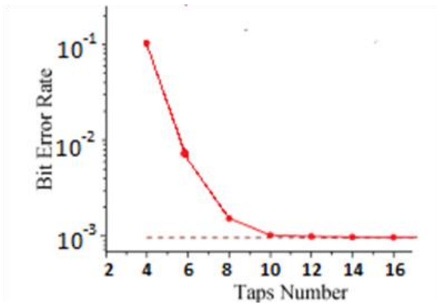
The frequency spectrum of dual carrier PolMux RZ-DQPSK and dual carrier PolMux NRZ-DQPSK systems at the receiver side after MZI filter is represented by Fig. 5. The spectra of 28 Gbaud PolMux NRZ-DQPSK and PolMux RZ-DQPSK signal is compared and it is found that the main spectral and side lobes of PolMux NRZ-DQPSK system are much narrower and more suppressed than PolMux RZ-DQPSK. Therefore, dual carrier PolMux RZ-DQPSK gives more Inter-symbol-Interference (ISI) between the two carriers as there is more spreading of lobes, in contrast to dual carrier PolMux NRZ-DQPSK systems.

4.2. CD equalization

LMS adaptive filter is used for CD equalization in the proposed communication systems at a device angle of 0^0 in SSMF over 20 km having CD coefficient of 16 ps/nm/Km. The performance of three different digital filters namely LMS adaptive filter, Finite-Impulse Response (FIR) filter and Blind Look-up filter for different fiber lengths in order to compensate for CD is investigated in [12-14] and conclusions show that adaptive LMS filter gives the best results among them for 20 km. Also, it is more tolerant towards phase noise than the other two filters [15-20]. Thus, the BER is plotted for different number of taps in the LMS filter for channel 1 in the systems under investigation in Fig. 6. It is of significance to note that in Fig. 6(a), for BER of 10^{-3}, the taps number required for PolMux NRZ-DQPSK system is 9 whereas for PolMux RZ-DQPSK system, it is 10. The results for PolMux NRZ-DQPSK system are in accordance with the above reference. This shows that PolMux RZ-DQPSK system has more BER for the same taps number as it attains a constant BER on a later stage than PolMux NRZ-DQPSK.



a

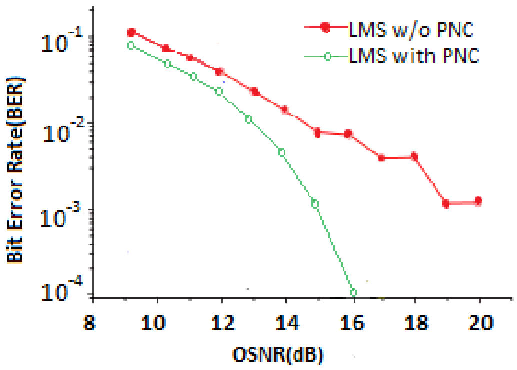


b

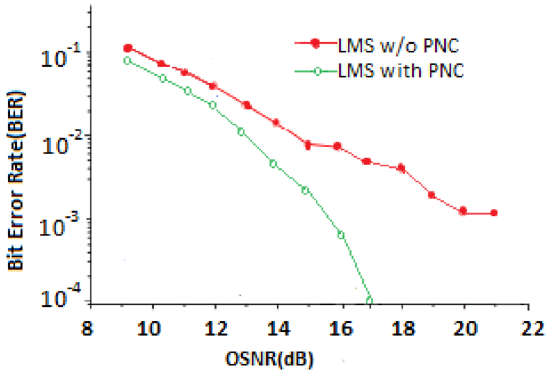
Fig. 6. BER vs. Taps number for back-to-back measurement using LMS adaptive filter in channel1 (a) PolMux NRZ-DQPSK system, (b) PolMux RZ-DQPSK system

4.3. Phase noise compensation

As discussed earlier, EEPN affects the BER of both the proposed communication systems. So a normalized LMS filter with one-tap is utilised to compensate the phase noise to give satisfactory results in both the systems. Fig.7 gives a plot of BER vs. OSNR with and without phase noise compensation in both PolMux RZ-DQPSK and both PolMux NRZ-DQPSK systems. It is observed that after compensation, PolMux NRZ-DQPSK system gives a better performance in OSNR by approx. 1 dB than PolMux RZ-DQPSK system for BER $=10^{-3}$. The effect of PMD is not taken into account as the measurements are for a device angle of 0^0 in SSMF over 20 km.



a



b

Fig. 7. BER vs. OSNR using normalised LMS for (a) PolMux RZ-DQPSK system, (b) PolMux NRZ-DQPSK system

5. Conclusion

Multi- modulation formats can help to increase the robustness of optical transmission due to high data rate with respect to the symbol rate. DQPSK modulation when combined with PolMux enables transmission with high spectral efficiency. With respect to polarization effects, dual carrier PolMux NRZ-DQPSK gives better performance by 1.25 dB in OSNR for BER= 10^{-3} than dual carrier PolMux RZ-DQPSK system at transmission of 112 Gb/s in SSMF for 20 km but the performances of both the systems degrade when there is increase in polarization mismatch. PolMux RZ-DQPSK shows more rapid degradation in OSNR comparatively. Therefore, due to influence of PMD-related impairments, improvements in transmission tolerances are required, which pose a great challenge for their long haul transmission. LMS adaptive filter is used for CD equalization in both the investigated transmission systems and it is seen that PolMux NRZ-DQPSK system gives better results for less number of taps than its RZ counterpart. Also, it has narrow optical spectrum which dictates less ISI. Phase noise is compensated using one-tap normalised LMS filter which shows improved results than the ones without compensation. Conclusively, PolMux NRZ-DQPSK system demonstrates more improved results than PolMux RZ-DQPSK in the aspect of compensating the linear impairments in the fiber.

Besides the CD and phase noise compensation, the PMD-related impairments and the non-linearities in the optical fiber are not taken into account. So future efforts can be done to incorporate the effects due to non-linearity and PMD. Furthermore, the performance of higher modulation formats such as Quadrature Amplitude Modulation(QAM-16, QAM-64) can be analysed on the basis of same proposed architecture with compensation of both linear and non-linear impairments. But it is a noteworthy point that as the constellation points in the modulation scheme increases, the impact of EEPN is also enhanced.

References

[1] J. M. Kahn, K. P. Ho, IEEE J. Sel. Topics Quantum Electron. **10**(2), 259 (2004).

[2] P. Boffi, M. Ferrario, L. Marazzi, P. Martelli, A. Righetti, R. Siano, M. Martinelli, Opt. Express **16**, 13398 (2008).

[3] C. Porzi, G. Meloni, M. Secondini, L. Poti, G. Contestabile, A. Bogini, J. Lightw. Technol. **30**(18), (2012).

[4] Stefan Wabnitz, IEEE Photon Technol. Lett. **25**(3), 264 (2013).

[5] D. van den Borne, S. L. Jansen, E. Gottwald, P. M. Krummrich, G. D. Khoe, H. de Waardt, J. Lightw. Technol. **25**(1), 222 (2007).

[6] L. E. Nelson, H. Kogelnik, Opt. Express **7**(10), 350 (2000).

[7] D. van den Borne, N. E. Hecker-Denschlag, G. D. Khoe, H. de Waardt, J. Lightw. Technol. **23**(12), 4004 (2005).

[8] S. Tsukamoto, D. S. Ly-Gagnon, K. Katoh, K. Kikuchi, presented at the Opt. Fiber Commun. Conf. (OFC), Anaheim, CA, paper PDP29, 2005.

[9] M. Skold, B. E. Olsson, H. Sunnerud, M. Karlsson, Tech. Dig. Opt. Fiber Commun. Conf. (OFC/NFOEC), 2005.

[10] Gurpreet Kaur, M. S. Patterh, Optik-International Journal of Light and Electron Optics **125**(15), (2014).

[11] Tianhua Xu, Gunnar Jacobsen, Sergei Popov, Jie Li,

Ari T. Friberg, Yimo Zhang, Opt. Express **19**(8), 7756 (2011).
[12] Tianhua Xu, Gunnar Jacobsen, Sergei Popov, Jie Li, Evgeny Vanin, Ke Wang, Ari T. Friberg, Yimo Zhang, Opt. Express **18**(15), 16243 (2010).
[13] A. K. Garg, R. S. Kaler, Chinese Optics Letters **6**(4), 244 (2008).
[14] Bhatia, E. K. Singh, T. S. Kamal, R. S. Kaler, IET Optoelectronics **6**(5), 250 (2012).
[15] Surinder Singh, R. S. Kaler, Optik-International Journal for Light and Electron Optics **119**(6), 296 (2008).
[16] G. Kaur, R. S. Kaler, S. Singh, JETP Letters **105**(5), 1 (2017).
[17] T. Xu, J. Gunnar, P. Sergei, L. Jie, S. Sergey, Ari T. Friberg, Tiegen Liu, Yimo Zhang, Optik-International Journal for Light and Electron Optics **138**, 494 (2017).
[18] T. Xu, G. Liga, D. Lavery, B. C. Thomsen, S. J. Savory, R. I. Killey, P. Bayvel, Scientific Reports **5**, 13990 (2015).
[19] T. Xu, G. Jacobsen, S. Popov, J. Li, S. Sergeyev, A. T. Friberg, Y. Zhang, Optics Communications **334**, 222 (2015).
[20] R. Goyal, R. S. Kaler, Optical Fiber Technology **18**(6), 518 (2012).

*Corresponding author: rskaler@yahoo.com