Enhanced gain in S+C band utilizing TDFA-FRA hybrid amplifier in cascaded and parallel configurations at reduced channel spacings for DWDM systems

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Abstract Thulium is basically a rare earth element that can be used as a dopant material in amplifiers designed to particularly operate in S-band (1460 nm-1530 nm) region. Another important category of optical amplifiers is fiber Raman amplifier (FRA), which have the capability to operate in any communication band, provided pump power centered at appropriate wavelength is injected into it. In this work, we have simulated TDFA-FRA hybrid amplifiers operating in cascaded and parallel configuration at 0.8 nm, 0.4 nm and 0.2 nm channel spacings. A total of 5 continuous wave (CW) lasers operating at 1000 nm, 1040 nm, 1390 nm, 1410 nm and 1450 nm have been used for pumping purposes in the proposed TDFA-FRA hybrid amplifier configured in cascade as well as parallel configuration. It has been observed that enhanced gain > 19 dB in the region 1460 nm to 1570 nm (110 nm) region has been attained by employing proposed multi-pumped TDFA-FRA hybrid amplifier.

1. Introduction

In order to transport data at high speed, communication systems possessing large transmission capacities are required. This requirement of transmission capacities can be achieved by employing optical communication networks. It is a well-known fact that transmission signal in optical communication suffers degradation in terms of shape and power with the increase in distance. One way to address this signal degradation problem is with the help of optoelectronic repeaters. But optoelectronic repeaters suffer from a major drawback known as Optical to Electronic and electronics to Optical (O-E-O) conversion [1-5].

Another strategy to address this signal regeneration problem is to deploy optical amplifiers which can efficiently avoid costly O-E-O conversions and amplify the optical signal directly in the optical domain [2-7].

A large number of amplifiers like semiconductor optical amplifiers (SOA), optical parametric amplifier (OPA), fiber Raman amplifiers (FRA), erbium doped fiber amplifier (EDFA), thulium doped fiber amplifier (TDFA) and hybrid amplifiers (TDFA-FRA, EDFA-TDFA, FRA-EDFA) have been developed [8]. Hybrid amplifiers have proved to be successful candidate as regenerative elements in long haul dense wavelength division multiplexed (DWDM) systems.

In the current work, we have concentrated on TDFA-FRA hybrid amplifier. There are two types of TDFAs, first is silica based TDFA and other one is fluoride based TDFA. Silica based TDFA has shown good performance in long haul transmission systems, due to their inherent non-toxic nature, easy manufacturing and splicing technology. But it has few problems such as low gain and non-uniform gain curve. Silica based TDFA also has a few disadvantages such as low gain at low pump powers due to presence of high phonon energy. This disadvantage of silica host is absent in fluoride host, as fluoride host gives high gain at low values of pump powers [9].

Thomas et al. (2001) [10] designed hybrid amplifier for short wavelength amplification by cascading TDFA with FRA. Maximum gain of 35 dB was obtained without the use of any flattening techniques due to symmetry of gain spectra of TDFA and FRA.

Perlin and Winful (2002) [11] designed a novel method in which multi wavelength pumped Raman amplifiers with optimal gain-flatness was proposed. In this relative gain flatness below 1% was achieved over bandwidths of 10- to-12 THz without using any gain equalization device.

Gomes et al. (2003) [12] discussed the characterization of dual-wavelength pumping scheme for the Thulium-doped fiber amplifiers (TDFA). Gain of 27 dB and noise figure of 5 dB was obtained.

Lüthi, et al. (2005) [13] cascaded one FRA and one or two Tm3+-doped fiber amplifier and designed a hybrid amplifier using a single pump. The gain over the entire band width and peak gain up to 24 dB and NF of 7 dB was achieved. No additional filters were used for gain flattening.

Aozasa et al. (2007) [14] clarified difference between single and double pass configurations for TDFA and established the superiority of dual-pass configuration over single-pass configuration with respect to the power-

conversion efficiency, where as it is inferior with respect to noise figure (NF).

Singh et al. (2012) [15] investigated the effect of several pumping options like single, two and seven in counter propagation mode in FRAs.

Emami et al. (2014) [16] proposed an extended method for the gain enhancement in S-band by using Thulium doped- Photonic crystal fiber amplifier (TD-PCFA) and shown by numerical simulations.

Singh and Singh (2016) [17] inspected the gain flatness for TDFA-FRA hybrid configuration by considering channel spacing of 5 nm. Maximum gain of 31.1 dB at 1470 nm and was observed.

As per our knowledge and after observing open literature available, it has been learnt that, no previous work has been done on characterization of TDFA-FRA hybrid amplifiers in S & C bands for ultra-narrow channel spacing of 0.8 nm, 0.4 nm and 0.2 nm.

The prime motivation behind the present work is to develop efficient optical amplifier which has apt ability to exhibit sufficiently wide gain spectrum in S & C bands with acceptable noise figure characteristics.

So, in this work, we have focused on attainment of enhanced gain utilizing TDFA-FRA amplifier utilizing cascaded as well as parallel configurations for ultra-narrow channel spacings of 0.8 nm, 0.4 nm and 0.2 nm with no gain flattening filter being used. For TDFA, pumping schemes with single pump, dual pump [18], and triple pump [17] have been presented in the past by several researchers. Further, in our previous work, we have optimized the performance of TDFA in the scenario of single/dual pumping [19]. Now, in our proposed hybrid amplifier, dual pumping (1000 nm & 1040 nm) for TDFA [19] and triple pumping (1390 nm, 1410 nm & 1450 nm) for FRA amplifier has been used. It has been observed that the gain of FRA amplifier depends on the pump wavelength and pump power, this effect has been used for enhancement of overall gain spectra of proposed cascaded/parallel hybrid amplifier. The gain spectrum of multi pumped TDFA-FRA hybrid amplifier has been evaluated at three different channel spacings (0.8 nm, 0.4 nm and 0.2 nm).

This article is organized as follows: In section 1, a brief introduction of amplifiers has been presented along with literature survey. Section 2 of this paper elucidates simulation setups of TDFA-FRA in cascade and parallel configuration along with parameters used in simulation study. In section 3, results and discussions have been presented. Conclusion are addressed in section 4.

2. System setup

In order to the evaluate gain spectrum of TDFA, FRA hybrid amplifier we have used optisystem 14 simulation tool. Fig. 1 shows simulation setup of TDFA-FRA hybrid amplifier in cascaded configuration.
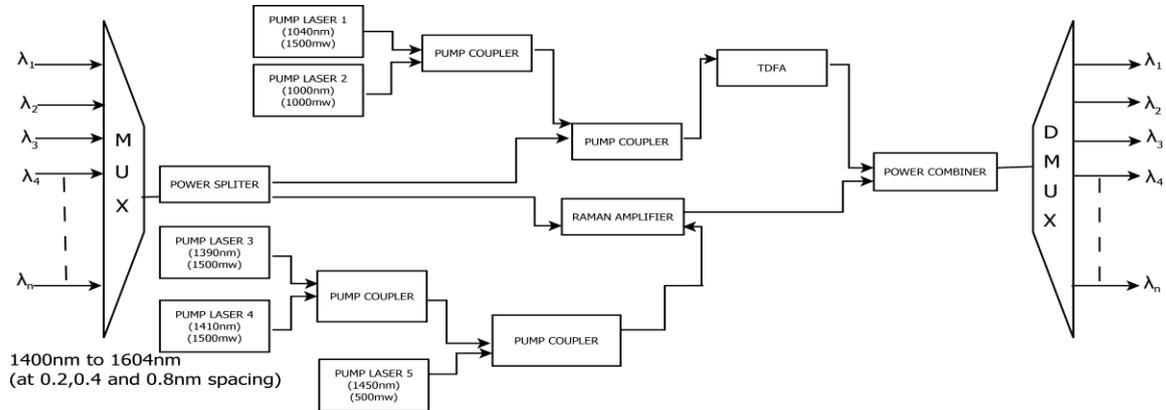
Fig. 1. TDFA-FRA hybrid amplifier in cascaded configuration.

As shown in Fig. 1, on transmitter side different channels ranging from 256 to 1000 each (depending on frequency spacing used (0.2 nm, 0.4 nm or 0.8 nm) ranging from 1400 nm to 1604 nm with peak power of -20 dB are used. Each channel is intensity modulated with 10 Gbps NRZ data generated by respective pseudo random binary sequence generators (PRBSs). These transmitted signals are multiplexed together by a typical multiplexer. A 3-dB power splitter is employed in order to split total power equally between FRA and TDFA as shown in Fig. 1.

FRA with triple pumps at wavelengths of 1390 nm at pump power of 1500 mW, 1410 nm at pump power of 1500 mW and 1450 nm at pump power of 500 mW have been utilized and afterward coupled together by pump coupler in a counter-propagating configuration. TDFA with pump wavelengths of 1000 nm and 1040 nm [19] have been utilized and afterward coupled together by pump coupler in a co-propagating configuration as shown in Fig. 1. The parameter values used of TDFA and FRA in proposed cascade and parallel structures are illustrated in Table 1 [19] as follows.

Table 1. Parameters values used for RAMAN and TDFA amplifiers [19]

	Parameter	Value
FRA	Length	10 km
	Attenuation	0.2 dB/km
	Effective interaction area	72 μm^2
	Raman gain peak	1×10^{-13}
	Rayleigh back scattering	5×10^{-5} km^{-1}
TDFA	Length	75 m
	Core radius	1.3 μm
	Doping radius	1.3 μm
	Numerical aperture	0.7
	Thulium ion density	1.68×1024 m-3

Further, Fig. 2 show the block diagram of TDFA-FRA hybrid amplifier in parallel configuration as follows.

It can be observed from Fig. 2 that almost all parameters values are similar as that used for cascaded configuration. The only difference between cascaded and parallel configuration is that in parallel configuration only a few channels covering the region 1400 nm to 1470 nm are injected into TDFA amplifier. Whereas, rest of channels spanning wavelength spectrum ranging from 1470 nm to 1604 nm are injected separately in to triple pumped FRA amplifier.
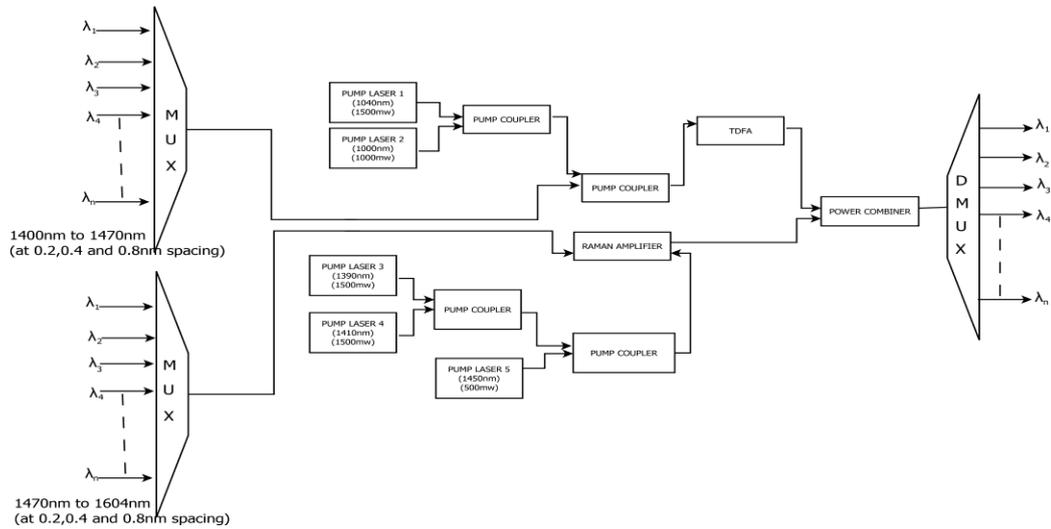
Fig. 2. TDFA-FRA hybrid amplifier in parallel configuration

3. Results and discussions

Combining TDFA with FRA is extremely effective approach, in light of the fact that FRA amplifier can give gain bandwidth in desired wavelength region/band by choosing the proper pump wavelengths. In any case, a downside with FRA amplifier is double Rayleigh scattering (DRS) which usually degrades the enhanced signals. The working wavelength of this amplifier covers the BW of whole short wavelength band (S-band) region by consolidating the gain range of TDFA and FRA.

The gain of TDFA-FRA hybrid amplifier has been obtained in both cascade and parallel configuration at ultra-narrow channel spacings of 0.8 nm, 0.4 nm and 0.2 nm.

3.1. Comparative assessment of gain spectrums for parallel and cascaded configurations

Case 1 – 0.8 nm spacing: In this case, gain spectrums for parallel and cascaded configurations at 0.8 nm channel spacings have been simulated and are presented in Fig. 3 as follows.
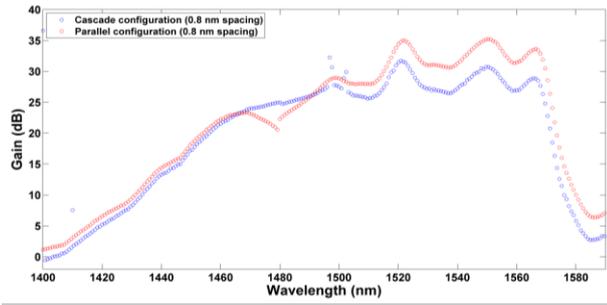
Fig. 3. Gain spectra of TDFA-FRA hybrid amplifier in cascade and parallel configuration at 0.8 nm channel spacing

The gain spectra of optimized TDFA-FRA hybrid amplifier cascaded as well parallel configurations at 0.8 nm spacing is shown in Fig. 3. It has been observed from the study of literature and preliminary simulation studies that gain of TDFA amplifier is better in the region < 1470 nm, whereas, in region 1470 to 1600 nm, the gain of FRA amplifier is much better as compared to TDFA. So, in the parallel configuration, the TDFA is fed with channels ranging from 1400 nm to 1470 nm (93 channels of TDFA are used), whereas, rest of all channels ranging from 1470 nm 1604 nm (164 channels of FRA are used), are inserted inside FRA amplifier. From Fig. 3, it is clear that overall gain of FRA amplifier is better as compared to TDFA. Maximum gain achieved in cascade form is 31.71 dB at 1520.8 nm with NF of 7 dB. Whereas, maximum gain achieved for TDFA-FRA parallel configuration is 35.23 dB at 1550.4nm region with NF of 7 dB.

Case 2 – 0.4 nm spacing: In this case gain spectrums for parallel and cascaded configurations at 0.4 nm channel spacings have been simulated and are presented in Fig. 4 as follows.
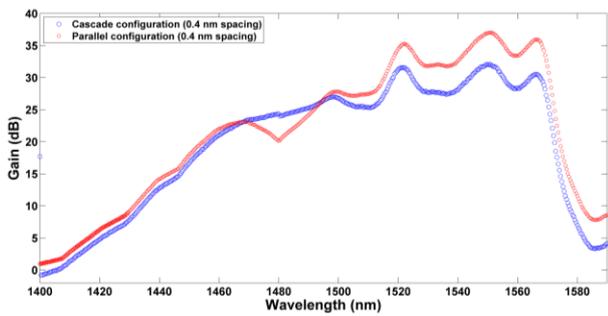
Fig. 4. Gain spectra of TDFA-FRA hybrid amplifier in cascade and parallel configuration at 0.4 nm spacing

The gain spectra of optimized TDFA-FRA hybrid amplifier cascaded as well parallel configurations at 0.4 nm spacing is shown in Fig. 4. As discussed earlier, in the

parallel configuration, the TDFA is fed with channels ranging from 1400 nm to 1470 nm (186 channels of TDFA are used), whereas, rest of all channels ranging from 1470 nm 1604 nm (328 channels of FRA are used), are injected inside FRA amplifier. From Fig. 4, it is evident that overall gain spectrum of FRA amplifier is far better as compared to that of TDFA. Maximum gain achieved in cascade form is 32.08 dB at 1550.8 nm with NF of -100 dB. Whereas, maximum gain achieved in parallel configuration is 36.91 dB at 1551.6 nm region with NF of 6.5 dB.

Case 3 – 0.2 nm spacing: In this case gain spectrums for parallel and cascaded configurations at 0.2 nm channel spacings have been simulated and are presented in Fig. 5 as follows.
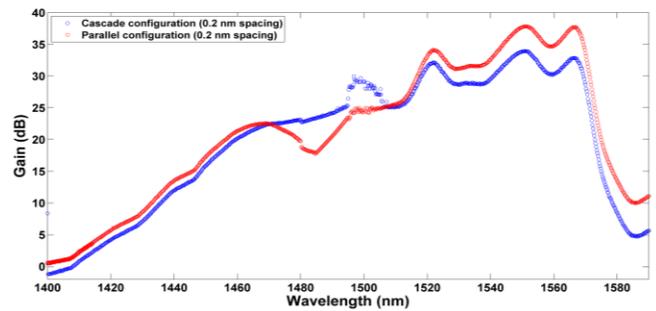
Fig. 5. Gain spectra of TDFA-FRA hybrid amplifier in cascade and parallel configuration at 0.2 nm spacing

The gain spectra of optimized TDFA-FRA hybrid amplifier cascaded as well parallel configurations at 0.2 nm spacing is shown in Fig. 5. As discussed earlier, in the parallel configuration, the TDFA is fed with channels ranging from 1400 nm to 1470 nm (372 channels of TDFA are used), whereas, rest of all channels ranging from 1470 nm 1604 nm (628 channels of FRA are used), are launched inside FRA amplifier. From Fig. 5, it is evident that overall gain spectrum of FRA amplifier is far better as compared to that of TDFA. Maximum gain achieved in cascade form is 33.95 dB at 1551 nm with noise figure of -100 dB. Whereas, maximum gain achieved in parallel configuration is 37.85 dB at 1564.2 nm region with noise figure of 10 dB.

3.2. Comparative assessment of gain spectrums for cascaded configuration at different channel spacings

The gain spectrums for cascaded configuration at different channel spacings (0.2 nm, 0.4 nm and 0.8 nm) have been presented in Fig. 6 as follows:
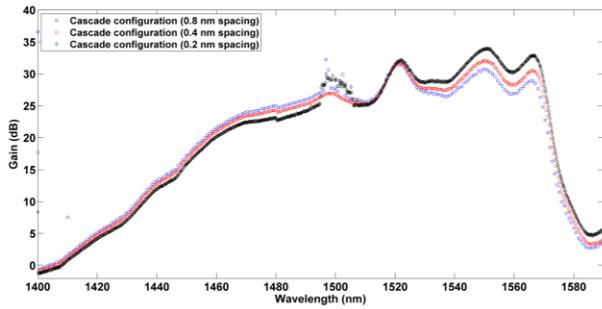
Fig. 6. Gain spectra of TDFA-FRA hybrid amplifier in cascade configuration at different channel spacings (0.2 nm, 0.4 nm & 0.8 nm)

Fig. 7. Gain spectra of TDFA-FRA hybrid amplifier in parallel configuration at different channel spacings (0.2 nm, 0.4 nm & 0.8 nm)

It can be noticed from Fig. 6, that as channel spacing is decremented or in other words more number of channels is transported in same bandwidth, the overall gain in the region (1500 nm to 1600 nm) decreases. This behavior can be attributed to occurrence of a non-linear effect know as four-wave mixing (FWM), which usually dominates at lesser channel spacings. Further, it can be observed from Fig. 6, that gain ≈ 20 dB in the region 1460 nm to 1570 nm (bandwidth = 110 nm) has been achieved for channel spacings 0.4 nm and 0.2 nm.

3.3. Comparative assessment of gain spectrums for parallel configuration at different channel spacings

The gain spectrums for parallel configuration at different channel spacings (0.2 nm, 0.4 nm and 0.8 nm) have been presented in Fig. 7 as follows:

It can be noticed from Fig. 7 that as channel spacing is decreased, the overall gain in the region (1500 nm to 1600 nm) decreases. As explained earlier this behavior is credited to occurrence of FWM effect in optical fiber used in FRA amplifier deployed in proposed hybrid amplifier structure. Further, it can be noticed after observing Fig. 6 & 7, that much flat gain spectrum with gain ≈ 20 dB, has been attained in the case of cascade configuration as compared to in parallel configuration for almost all channel spacings. So, it can be said, cascade configuration is much better as compared to parallel configuration in terms of gain flatness.

Further, in order to illustrate, the level of development achieved using the proposed hybrid TDFA-FRA amplifier, a comparison with earlier reported amplification schemes is presented in Table 2 as follows.

Table 2. Comparison of proposed hybrid TDFA-FRA amplifier with earlier reported amplification strategies

Author Name and year	Parameters					Filters used
	Amplifier used	Amplification window (nm)	No. of pumps used	Gain (dB)	Noise Figure (dB)	
Thomas et al. (2001) [10]	TDFA-FRA	1445-1520	3	20	7-8	No
Gomes et al. (2003) [12]	TDFA	1456-1584	2	27	5	-
Lüthi et al. (2005) [13]	TDFA-FRA	1460-1530	1	24	7	No
Kakkar et al. (2006) [18]	TDFA	1604-1636	1	20	0.3	Discrete filters
Aozasa et al. (2007) [14]	TDFA	1480-1510	2	26	7	-
Singh et al. (2012) [15]	FRA	1535-1584	7	-	-	No
Singh and Singh (2016) [9]	TDFA-FRA	1460-1510	3	31	-	No
Present work	TDFA-FRA	1400-1604	5	36.91	6.5	No

It can be observed from Table 2, that proposed TDFA-FRA hybrid amplifier can amplify a wider range of signals (110 nm) as compared to some earlier strategies such as Thomas et al. (2001) [10], Lüthi et al. (2005) [13], Kakkar et al. (2006) [18], Aozasa et al. (2007) [14], Singh et al.

(2012) [15], Singh and Singh (2016) [9]. Further, it has been also observed that proposed TDFA-FRA hybrid amplifier requires lesser CW lasers as pump sources as compared to following strategy proposed by Singh et al. (2012) [15].

Further research studies can be carried out in order to flatten the gain of proposed TDFA-FRA hybrid amplifier strategies by either utilizing gain flattening filters or any other parameter optimization strategy.

4. Conclusions

In this work, enhanced gain $\approx$ 20 dB in the region 1460 nm to 1570 nm region has been demonstrated for TDFA-FRA hybrid amplifier in cascaded and parallel configurations. A dual pumped TDFA with following pump wavelengths: 1000 nm & 1040 nm along with a triple pumped FRA with following pump wavelengths: 1390 nm, 1410 nm and 1450 nm has been utilized in proposed hybrid amplifier. It has been shown that at 0.4 nm spacing, the TDFA-FRA hybrid amplifier arranged in cascaded configuration exhibits overall enhanced gain with minimum and maximum of is 19.15 dB and 19.84 dB, in region 1455 to 1572 nm and with peak gain of 32.08 dB at 1550.8 nm. Further, Maximum gain attained in parallel configuration is 36.91 dB at 1551.6 nm region with NF of 6.5 dB. It has been observed that overall gain of cascaded configuration is much flatter as compared to parallel configuration in the region (1470 nm to 1590 nm) at 0.4 nm and 0.2 nm spacings.

References

[1] B. Mukherje "Optical WDM Networks" Springer, New York, 2006.

[2] K. Singh, G. Kaur, M. L. Singh, Opt. Eng. **55**(7), 077104 (2016).

[3] K. Singh, G. Kaur, M. L. Singh, Opt. Quantum Electron. **48**(9), 418 (2016).

[4] K. Singh, G. Kaur, M. L. Singh, Optoelectron. Adv. Mat. **11**(3-4), 189 (2017).

[5] K. Singh, G. Kaur, M. L. Singh, Photon. Netw. Commun. **34**(11), 111 (2017).

[6] K. Singh, G. Kaur, M. L. Singh, Opt. Fiber Technol. **24**, 56 (2015).

[7] K. Singh, G. Kaur, Opt. Laser Technol. **69**, 122 (2015).

[8] G. P. Agrawal, "Fiber Optic Communication Systems", John Wiley and Sons, New York, 1997.

[9] R. Singh, M. L. Singh, In International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT), 2016, 164-167.

[10] J. M. Thomas, D. Crippa, A. Maroney, In Optical Fiber Communication Conference and Exhibit, 2001, WDD9-WDD9.

[11] V. E. Perlin, H. G. Winful, J. Lightwave Technol. **20**(2), 250 (2002).

[12] A. S. Gomes, M. T. Carvalho, M. L. Sundheimer, C. J. Bastos-Filho, J. F. Martins-Filho, M. C. e Silva, J. P. Von der Weid, W. Margulis, IEEE Photon. Technol. Lett. **15**(2), 200 (2003).

[13] S. R. Luthi, M. C. Silva, C. J. Bastos-Filho, J. F. Martins-Filho, A. S. Gomes, IEEE Photon. Technol. Lett. **17**(10), 2050 (2005).

[14] S. Aozasa, H. Masuda, M. Shimizu, M. Yamada, J. Lightwave Technol. **25**(8), 2108 (2007).

[15] K. Singh, M. S. Patterh, M. S. Bhamrah, Int. J. Computer Appl. **39**(4), 11 (2012).

[16] S. D. Emami, A. R. Muhammad, S. Z. Muhamad-Yasin, K. A. Mat-Sharif, M. I. Zulkifli, F. R. Adikan, H. Ahmad, H. A. Abdul-Rashid, IEEE Photon. Technol. Lett. **6**(6), 1 (2014).

[17] R. Singh, M. L. Singh, B. Kaur, Opt.-Int. J Light Electron Opt. **123**(30), 1815 (2012).

[18] C. Kakkar, G. Monnom, K. Thyagarajan, Opt. Commun. **262**(2), 193 (2006).

[19] P. Kaur, K. Singh, S. Devra, G. Kaur, M. L. Singh, J. Opt. Commun. (Accepted-in press). (doi: 10.1515/joc-2017-0100)

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