Bidirectional Fiber Bragg grating-circulator based optical add-drop multiplexer in DWDM transmission system with reduced channel spacing at 40 Gb/s

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In this paper, unique structure of an optical add-drop multiplexer (OADM) based on bidirectional Fiber Bragg Grating-Optical circulator (FBG-OC) has been investigated for dense wavelength division multiplexed system with different modulators like Amplitude Modulator (AM), Mach-Zehnder (MZ) and Electro absorption (EA). This investigation has been done at 40 Gbps/ channel with ultra-narrow channel spacing of 0.1 nm. Using AM modulator, the maximum distance can be achieved over 70 Km with acceptable BER performance. It is reduced to 50 and 30 Km with MZ and EA respectively. In addition, it is also observed that the structure provides acceptable BER performance with maximum FBG bandwidth of 280 GHz and insertion loss of 9 dB, circulator insertion loss of 4.5 dB for Amplitude Modulator.

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1. Introduction

Optical add-drop multiplexer (OADM) will play a key role in enabling greater connectivity and flexibility in dense wavelength-division multiplexing (DWDM) networks [1, 2]. Fiber-Bragg-grating (FBG)-based devices [3] seem to be promising for OADMs because of their advantages such as small size, inherent low loss, spectral selectivity, and cylindrical symmetry permits easy coupling with optical fiber systems. Fiber gratings can be used in extremely narrow band filters, fiber lasers, dispersion compensators [4], wavelength converters [5], phase conjugators, add/drop multiplexers and wavelength stabilized pump lasers [6]. The propagating wave is reflected, if its wavelength equals Bragg resonance wavelength, λ_{Bragg}. Otherwise, the wave is transmitted. The equation relating the grating spatial periodicity and the Bragg resonance wavelength is given by [7],

$$\lambda_{Bragg} = 2\, \eta_{eff}\, \Lambda \qquad (1)$$

where λ_{Bragg} is Bragg resonance wavelength, n_{eff} is effective mode index and Λ is grating period. FBG devices are reflective devices and the dispersion spectrum can be defined independently from the reflection spectrum. Y. K. Chen et al. [8] proposed and investigated three kinds of low-crosstalk and compact optical add-drop multiplexers (OADMs) based on a multiport optical circulator (MOC) with fiber Bragg gratings. For the MOC-based structure, there was a significant intra band crosstalk reduction of about 37 and 16 dB on the dropped and added channels, respectively, for the best proposed MOC-based structure as compared with the conventional structure. Bit-error rate performance and both intra band and inter band crosstalk-induced power penalties of these MOC-based OADMs are examined in a 10-Gb/s system demonstration with 1.6 nm channel spacing. S.K. Narayankhedkar et al. [9] studied the crosstalk performance of fiber Bragg gratings (FBG) based optical add/drop multiplexer for the dense wavelength division multiplexed (DWDM) system using 0.8 nm channel spacing at 10 Gb/s. M. Mahiuddin et al. [10] developed an analytical model to study the incoherent crosstalk of a fiber Bragg grating based OADM. Results showed that crosstalk, power penalty, relative intensity noise and bit error rate are minimum when the signals are added at Bragg wavelength and improve the system performance significantly. Jungho Kim et al. [11] proposed and experimentally demonstrated a new structure of bidirectional wavelength add–drop multiplexer using multiport optical circulators and fiber Bragg gratings. It has the sufficient suppression of the unwanted light caused by Rayleigh backscattering and optical reflection and is economical for the effective use of multiport optical circulators. An Vu Tran et al. [12] proposed and demonstrated a new bidirectional optical add–drop multiplexer (BOADM) with gain based on multiport optical circulators and fiber Bragg gratings. The BOADM incorporates a single unidirectional optical amplifier and could flexibly accommodate asymmetric traffic. The device achieved more than 13 dB of bidirectional gain and has low in-band crosstalk (below -45 dB) and low out-of-band crosstalk (below -30 dB). Unfortunately, all of them either use large channel spacing (> 12.5 GHz) at lesser bit rate or significantly increase the complexity and cost of the specific laser source and optical components. Hai Yuan et al. [13] proposed a new bidirectional optical cross connect (BOXC) using fiber Bragg gratings (FBGs) and optical circulators for bidirectional wavelength-division-multiplexing ring networks. Dynamic and independent wavelength routing was achieved by employing cascaded tunable FBGs. Chen-Mu Tsai et al. [14] proposed a bi-directional reconfigurable scheme of multichannel-selective optical add–drop multiplexer (OADM). With only small wavelength channel tuned range, the proposal applied fiber Bragg gratings (FBGs) and multiport optical circulators (MOCs) to build a bi-direction reconfigurable OADM which could deal with full channels without the receiving signal having wavelength-interleaved. Moreover, it was easier and more flexible to extend wavelength channels by cascading additional FBGs. Xuefang Zhou et al. [15] proposed and demonstrated a reconfigurable optical add-drop multiplexer (OADM) architecture using a single multiport optical circulator (MOC) and several narrow band fiber Bragg gratings (FBGs) at 10Gb/s to represent three WDM channels. The proposed OADM consists of a single 7-port circulator and two pairs of identical FBGs.

In this paper, the structure of Bidirectional FBG-OC (Fiber Bragg Grating-Optical circulator) based OADM is proposed and investigated. The effect of FBG bandwidth, insertion loss of FBG and optical circulator are evaluated using three kinds of modulators in DWDM transmission system at 40 Gb/s with 0.1nm channel spacing. Our proposed system setup shows improvement over conventional OADM where one FBG is used and reported in [10]. After the introduction, Analysis of Optical modulators is described in Section II, a system set up is described in Section III. Section IV explains the results and discussion and Section V summarizes the conclusion.

2. Analysis of optical modulators

In this paper, three modulators AM, EA and MZ have been used and compared. The basic principle of all optical modulators is to modulate the optical carrier according to the data signal in the term of amplitude, frequency, phase etc. The general schematic of optical modulator is shown in Fig. 1.

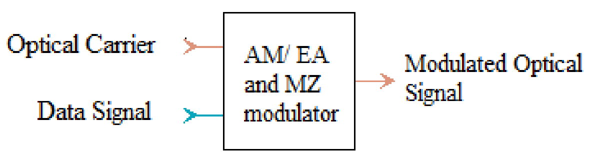

Fig. 1. Schematic of optical modulator

Amplitude Modulator:

The output signal $E_{out}(t)$is given by [16]

$$E_{out}(t) = E_{in}(t).\sqrt{d(t)} \tag{2}$$

where $E_{in}(t)$ denotes the input optical signal. The power transfer function d(t) is defined as:

$$d(t) = (1 - m) + m.data(t) \tag{3}$$

where m is the Modulation Index and data(t) represents the electrical modulation signal. It is assumed that usually data(t) varies within the limits $0 \le data(t) \le 1$ to ensure a power transfer function d(t) larger than zero. If a negative power transfer function d(t) would arise, d(t) is internally clipped up to zero. The power of the output signal $P_{out}(t) = |E_{out}(t)|^2$ is given by:

$$P_{out}(t) = P_{in}(t).d(t) = P_{in}(t).\big((1 - m) + m.data(t)\big) \tag{4}$$

with $P_{in}(t) = |E_{in}(t)|^2$ being the input power of the optical carrier, as shown in Fig. 2:

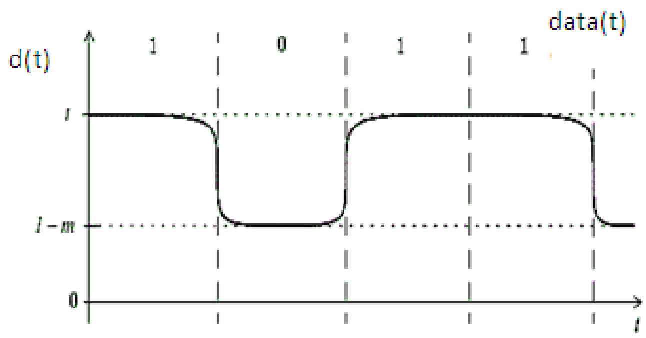

Fig. 2. Power transfer function of the AM-modulator for the rectangular-like modulation signal varying in the range from 0 to 1

Basic specifications and its considered values:

Specification (Parameter)	Value
ModulationIndex (m)	1
Input power of the optical carrier ($P_{in}(t)$)	1 mW

Electro absorption Modulator:

The output signal $E_{out}(t)$ is given by

$$E_{out}(t) = E_{in}(t).\sqrt{d(t)}.exp\left(\frac{j\alpha}{2}ln[d(t)]\right) \tag{5}$$

where $E_{in}(t)$ is the input optical signal and α denotes the Chirp Factor which couples the phase and amplitude changes of the optical wave [16]. To represent the power transfer function d(t) power of the output signal $P_{out}(t)$, the previous reported equation (3) and (4), are used respectively.

Basic specifications and its considered values:

Specification (Parameter)	Value
ModulationIndex (m)	0.9
Chirp Factor (α)	0
Input power of the optical carrier ($P_{in}(t)$)	1 mW

Mach-Zehnder modulator:

This module represents a Mach-Zehnder modulator with a single RF drive port as shown in Fig. 3. The behavior of such modulators depends on their design, and specifically the configuration of the electrodes with respect to the Lithium-Niobate crystal. With good design and manufacturing [16, 17], the modulator will have a large extinction ratio, and a low chirp (dynamic change in frequency under modulation). This version includes a choice on specifying the chirp (the optical frequency shifts during the leading and trailing edges of a pulse).

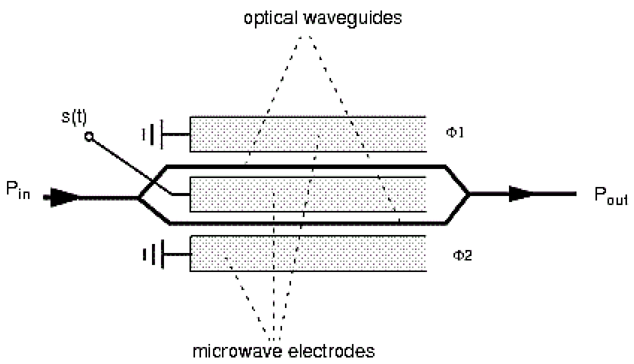

Fig. 3. Schematic of Mach-Zehnder modulator

The optical power P_{out} at the output of MZM, depends on the phase difference ΔΦ between the two modulator branches.

$$P_{out}(t) = P_{in}(t).d(t) = P_{in}(t).cos^2[\Delta\Phi(t)] \quad (6)$$

with

$$\Delta\Phi(t) = \frac{\Delta\Phi_1(t) - \Delta\Phi_2(t)}{2}$$

where d(t) is the power transfer function and $\Delta\Phi_1(t)$ and $\Delta\Phi_2(t)$ are the phase changes in each branch caused by the applied modulation signal data(t).

Basic specifications and its considered values:

Specification (Parameter)	Value
Extinction ratio	30 dB
Symmetry Factor (A physical-design based parameter for specifying the chirp)	-1
ChirpSign (A physical-design based parameter for specifying the chirp. Takes the opposite sign of the AlphaFactor)	Positive

These specifications and models have been used in numerical simulations.

3. Numerical simulation set up

The proposed DWDM network consists of three stages i.e. transmitter, Bidirectional FBG-OC (Fiber Bragg Grating-Optical circulator) based OADM and receiver is shown in Fig. 4. The OADM has four ports namely input port, add port, drop port and output port. A first channel (ch-1) with one frequency is dropped to the drop port and the same frequency is added to the add port. Each transmitter is composed of data source, NRZ rectangular driver, laser source, optical amplitude modulator. Data source generates a binary sequence of data stream. The Continuous wave (CW) laser source is used to generate an optical carrier having 1 mW of power and 10 MHz of line width which is fed to the optical modulator. Modulation driver generates the non-return-to zero (NRZ) rectangular data signals with a signal dynamics (amplitude level variation) i.e. low level -2.5V and high level +2.5V. The pulses are then modulated using Amplitude Modulator (AM), Mach-Zehnder (MZ) and Electro Absorption (EA) modulator individually at 40 Gbps of data signals.

The transmitters are followed by a 4:1 combiner which combines four optical input channels and consists of three cross couplers and a fiber link with dispersion 16 ps/nm/km and core effective area 80 (10^ (-12) m^2). For adding and dropping operation, the inline bidirectional OADM is used which consists of two circulators and bidirectional filter FBG. Bidirectional filter FBG includes two basic FBG filters and two multiplexer which reflect as well as transmit the wavelength with two bidirectional ports and allow transmission in both directions as shown in Fig. 5. The parameters of FBG and circulator (such as circulator insertion loss, FBG insertion loss, FBG bandwidth) have been taken as variable. Other related fixed parameters are FBG and circulator rejection of 30 dB is used.

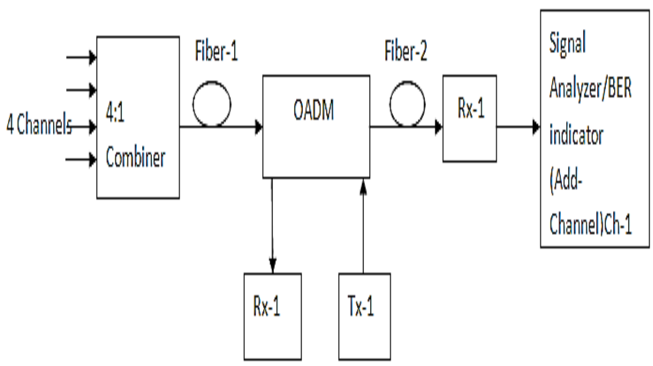

Fig. 4. System Set up

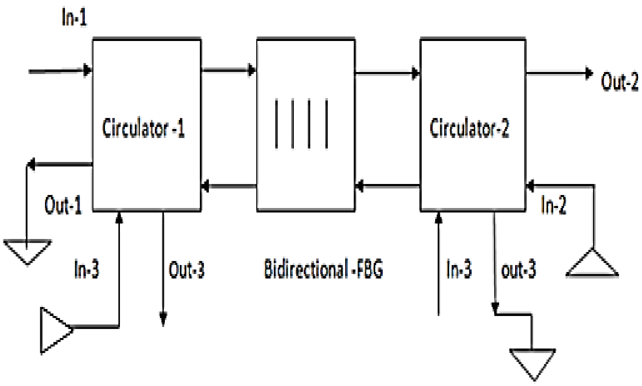

Fig. 5. A typical Add/Drop multiplexer

In a three-port circulator, an input signal on port 1 is sent out on port 2, an input signal on port 2 is sent out on port 3 and an input signal on port 3 is sent out on port 1. An informational signal is added at the add port, reflected back through fiber Bragg grating and passed through the output (circulator 2). Another signal with the same wavelength as the informational signal is entered at the input port (circulator 1). This signal is reflected through the grating and dropped at the drop port.

The receiver is composed of optical raised cosine band pass filter with 0.2 raised cosine roll off, center frequency of 192.2 THz, PIN photodiode with 1A/W responsivity, zero dark current and low-pass Bessel filter. Signal Analyzer is used to observe the performance.

4. Results and discussion

The performance of Bidirectional FBG-OC based OADM in terms of BER is recorded at first channel of the DWDM system using three modulators with the variations of transmission distance, FBG bandwidth, insertion loss of FBG and Circulator with 0.1 nm channel spacing at 40 Gb/s of speed. Fig. 6 shows the BER with transmission distance plot of add Channel ch-1 (192.2 THz) detected at output port. In this case the insertion loss of FBG and circulator is taken as 0 dB with the FBG bandwidth of 40 GHz. to check the impact of transmission distance. It is evident that the proposed network survives up to 70 Km transmission distance using A.M modulator giving acceptable BER of 8.90×10^{-12}. This result coincides with the result of M. Mahiuddin et al. [10] where it was reported that as number of added channel increases, the BER increases and for single channel added, the BER was near to 10^{-7}.Here we reported BER 10^{-12} for single channel added at 40 Gb/s for 70Km distance. This shows that the AM modulator provides wider coverage area and hence suitable for long distance communication. By using MZ and EA modulators, the network survives up to 50 Km and 30 Km distance for add Channel giving acceptable BER of 1.00×10^{-9} and 3.00×10^{-12}, after that the system performance is degraded since MZ and EA modulators are lumped electrode devices whose speeds are limited by the total parasitic of the devices, which restricts the devices to very short length for high speed operation and have more chirp.

Fig. 7 shows the BER with FBG bandwidth plot of frequency 192.2 THz (ch-1) at output port (add) for 30 Km distance. It is observed that the network can survive with larger FBG bandwidth up to 280 GHz for AM modulator with zero insertion loss of FBG and Circulator showing an acceptable BER 9.79 $\times10^{-10}$. With MZ and EA modulator, the System Survive up to FBG bandwidth of 240 GHz and 200 GHz providing an acceptable BER of 8.51 $\times10^{-10}$ and 9.26×10^{-10} respectively. After that the system performance is again degraded.

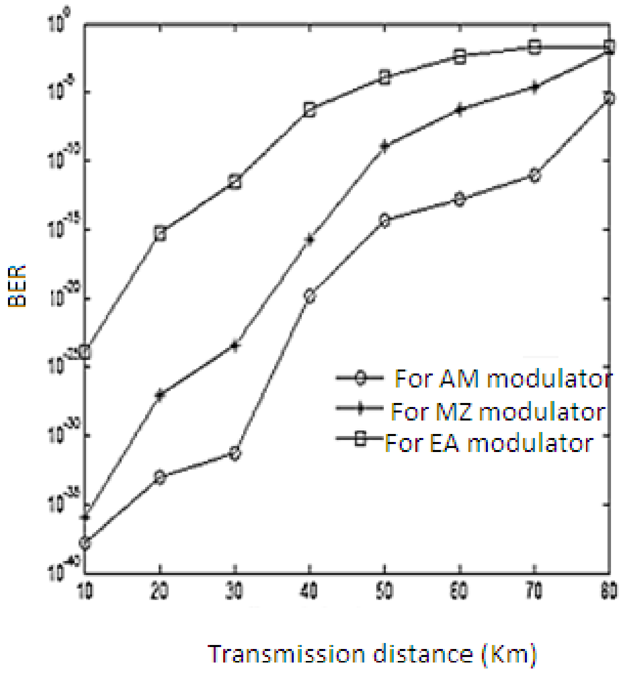

Fig. 6. BER v/s Distance plot of add channel at frequency 192.2 THz (ch-1)

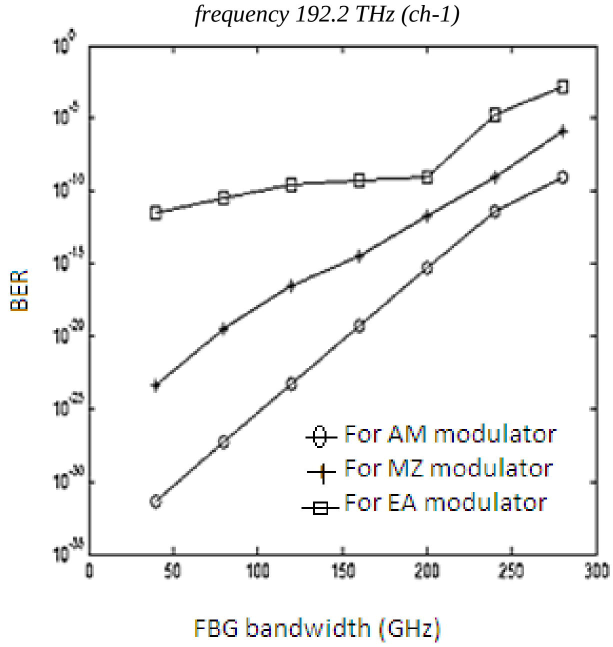

Fig. 7. BER v/s FBG B.W plot of add channel at frequency 192.2 THz (ch-1)

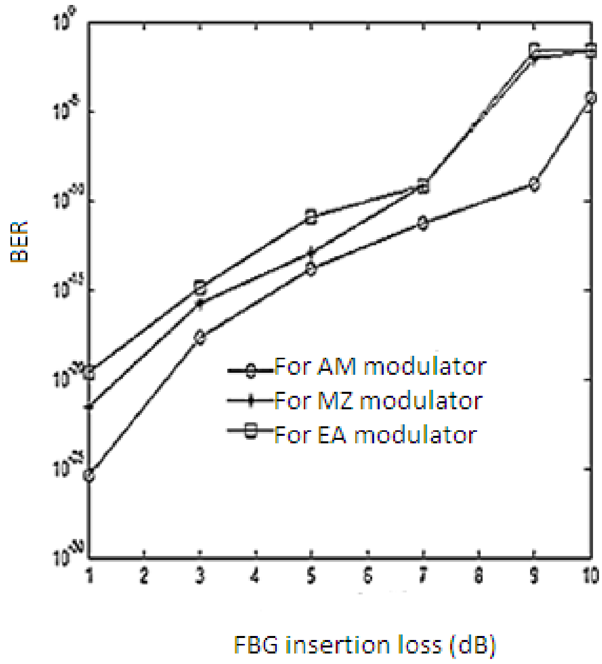

Fig. 8. BER v/s FBG I.L plot of add channel at frequency 192.2 THz (ch-1)

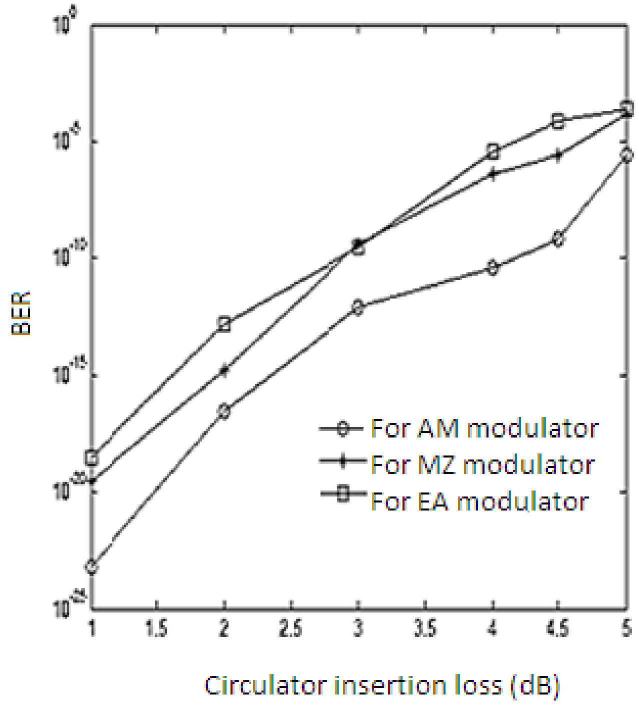

Fig. 9. BER v/s Circulator I.L plot of add channel at frequency 192.2 THz (ch-1)

Fig. 8 shows the BER with FBG insertion loss plot of frequency 192.2 THz (ch-1) at output port (add) for 30 Km distance with zero insertion loss of circulator. It is observed that the network can tolerate maximum insertion loss of 9 dB for AM modulator showing an acceptable BER of 8.16×10^{-10}. With MZ and EA modulators, the System can tolerate insertion loss up to 7 dB showing an acceptable BER of 7.24×10^{-10} and 6.53×10^{-10} respectively.

Fig. 9 shows the BER with circulator insertion loss plot of frequency 192.2 THz (ch-1) at output port (add) for 30 Km distance with zero insertion loss of FBG. It is observed that the network can tolerate an insertion loss up to 4.5 dB for AM modulator showing an acceptable BER of 6.16×10^{-10}. With MZ and EA modulators, the System can tolerate an insertion loss up to 3 dB showing an acceptable BER of 4.24×10^{-10} and 3.14×10^{-10} respectively.

5. Conclusion

We have proposed and investigated the structure of Bidirectional FBG–Optical Circulator based OADM for high speed DWDM networks with 0.1nm of interval. Three kinds of modulators have been used and further compared with respect to the variation of performance parameters including FBG bandwidth, insertion loss of FBG and optical circulator. Using MZ and EA modulators, the transmission distance is restricted to 50 Km and 30 Km while it is increased to 70 Km when the AM is utilized. It is observed that using AM modulator, the signal can be transmitted up to 70 km with an acceptable BER. In addition, it is also observed that the proposed system provides acceptable performance with maximum FBG bandwidth of 280 GHz, FBG insertion loss of 9 dB, circulator insertion loss of 4.5 dB for Amplitude Modulator.

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