Performance Analysis of Four Wave Mixing Based Wavelength Conversion in Commercial Optical Fibers

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Abstract- In this paper, we discussed on Four-wave-mixing (FWM) based wavelength conversion at 1.55 µm and 1.552 µm using six different types of commercial optical fibers. For a pump peak power of 6.2W, a numerical simulation is used to predict the performance of each type of fibers for different experimental conditions and to address the potential of each fiber type in wavelength conversion applications utilizing four-wave-mixing. It is shown that wavelength conversion, covering the entire C-band, can be achieved with different performance for each type of optical fiber at reasonable optical pump power.

The simultaneous wavelength conversion of two different formats or bit-rate optical signals, with low input power, is demonstrated in a highly nonlinear optical fiber with a single strong continuous-wave pump. The effect of four-wave-mixing at highly nonlinear optical fiber is analyzed at 1 km distances with its power. The Four Wave Mixing is analyzed in non-degenerate mode for wavelength conversion.

Index Terms- Four wave mixing (FWM), MZI modulator, SMF-28 single mode fiber, Positive dispersion non-zero dispersion-shifted fiber (LEAF), Negative dispersion non-zero dispersion-shifted fiber (METRO), Dispersion compensating fiber (DCF), Vascade Optical fiber (Sea Cable).

I. INTRODUCTION

The field of nonlinear optics has continued to grow at a tremendous rate since its inception in 1961 and has proven to be a nearly inexhaustible source of new phenomena and optical techniques. In optical communication systems the term nonlinearity refers to the dependency of the system on power of the optical beam being launched into the fiber cable. Nonlinear effects in optical fibers have become an area of academic research and of great importance in the optical fiber based systems. Several experiments in the past have shown that the deployment of high-bit-rate multi-wavelength systems together with optical amplifiers creates major nonlinear effects such as stimulated Raman scattering (SRS), stimulated brilliouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave-mixing (FWM). These effects have proven to be of utility in a great number of applications including pulse compression, solitons, optical tune able delays, optical switching, and pulse retiming and wavelength conversion.

In a wavelength-routed optical network, wavelength conversion plays a major role to reduce wavelength blocking, provide high flexibility and utilization of wavelength allocation in network management, which has been investigated extensively in the past several years. An all-optical approach of wavelength conversion is favorable to avoid bit-rate bottleneck and costly signal conversion between optical and electrical domains since current electronic processing speeds are approaching fundamental limits near 40Gb/s. Ultra-high data rate all-optical wavelength conversion is an enabling technology for providing wavelength flexibility, increasing the capacity of photonics networks and enhancing optimized all-optical routing and switching. Several all-optical wavelength conversion approaches have been demonstrated, which are based on nonlinearities in semiconductor optical amplifiers, in optical fibers, in crystals and so on. Among these approaches, wavelength conversion based on the nonlinearity of optical fibers is inherently featured of femto-second response time, low insertion loss, non-degraded extinction radio of the signal and low-noise characteristics, which shows the promising potential of achieving terabit-per-second performance. Nonlinear effects mainly applied in fiber-based wavelength conversion are XPM, FWM and SPM, all of which originate from the Kerr effect. Among the various nonlinear phenomena exploited for fiber-based wavelength conversion, FWM is regarded as advantageous due to its transparency both in terms of modulation format and bit rate. However to make use of this nonlinear phenomenon in optical signal processing requires that a suitable fiber be available.

In this paper, six commercial optical fibers to achieve a wavelength conversion covering the entire C-band have been analyzed and comparison is made in their performance using a simulator software Optisystem 9.0 from Optiwave Inc. The mathematical review presented is based on the theory and a numerical analysis of the wavelength conversion process is carried out. All optical wavelength conversion is considered as key components due to their main advantages which comprises increase in the flexibility, the capacity of networks besides facilitating WDM network management. Therefore the optical wavelength conversion based on FWM, one of the phenomenons's on fiber nonlinearities have been proposed and discussed and then its framework of application in optical communication networks based on complex meshes.

The objectives are discussed in this paper:

A. To study the Four Wave Mixing (FWM) phenomenon based wavelength conversion.

B. To investigate the performance of different commercial fibers for FWM based wavelength conversion in WDM system.

II. MATHEMATICAL REVIEW

The total polarization P is nonlinear with respect to the electric field E, however, it can be written as:

$$P = \varepsilon 0\,(\chi^{(1)} .E + \chi^{(2)} .E.E + \chi^{(3)} .E.E.E + \dots\dots)$$

Where, ε_0 is the vacuum permittivity and $\chi\ (j)\ (j = 1, 2\ \dots)$ is jth order susceptibility.

When light propagates in a transparent medium, its electric field causes some amount of polarization in the medium. While at low light intensities the polarization is linear with the electric field, nonlinear contributions become important at high optical intensities, so the polarization equation consists linear terms as well as nonlinear terms. The first order susceptibility $\chi^{(1)}$ represents the linear term, and nonlinearities can have strong effects in fibers at the third order susceptibility $\chi^{(3)}$. So, only the nonlinear effects in the optical fibers, which originate from the third-order susceptibility $\chi^{(3)}$, will be considered and the other terms will be neglected. The programming will start from the third-order susceptibility $\chi^{(3)}$. Thus the electric field of the signal can be written as:

$$E(r,t) = \varepsilon_0\, E_t \cos(\omega_1 t - \beta_t z)$$

Where, β is the propagation constant, and ω is angular frequencies.

Substituting Equation 4.2 into Equation 4.1, and if only the term of the third order susceptibility is taken into account, the nonlinear dielectric polarization is given as

$$P = \varepsilon_{0.}\chi^{(3)} \textstyle\sum_{i=1}^{n} (E_i .\cos(\omega_i t - \beta_i z).E_j.\cos(\omega_j t - \beta_j z).E_k.\cos(\omega_k t - \beta_k z)$$

$$= 3\frac{\varepsilon_0}{4}\chi^{(3} \textstyle\sum_{i=1}^{n} (E_i^2 + 2\sum_{i=1}^{n} (E_i E_j))\, E_i \cos(\omega_i t - \beta z)$$

$$+ \frac{\varepsilon_0}{4}\chi^{(3)} \textstyle\sum_{i=1}^{n} (E_i^3 \cos(3\omega_i t - 3\beta z)$$

$$+ 3\frac{\varepsilon_0\chi^{(3)}}{4} \textstyle\sum_{i=1}^{n} . \sum_{j=1}^{n} (E_i^2\, E_j \cos((2\omega_i t - 3\beta_i z)t - (2\beta_i - \beta_j)z)$$

$$+ 3\frac{\varepsilon_0\chi^{(3)}}{4} \textstyle\sum_{i=1}^{n} . \sum_{j=1}^{n} (E_i^2\, E_j \cos((2\omega_i t - 3\beta_i z)t - (2\beta_i - \beta_j)z)\ )$$

$$+ \frac{3\varepsilon_0\chi^{(3)}}{4} \textstyle\sum_{i=1}^{n} . \sum_{j=1}^{n} . \sum_{j=1}^{n} (E_i^2\, E_j\, E_k)$$

$$\cos(\omega_i + \omega_j + \omega_k)t - (\beta_i + \beta + \beta_k)z.\ \cos(\omega_i + \omega_j - \omega_k)t - (\beta_i + \beta_j - \beta_k)z$$
$$+\cos(\omega_i + \omega_j + \omega_k)t - (\beta_i + \beta_j + \beta_k)z + \cos(\omega_i - \omega_j + \omega_k)t - (\beta_i - \beta_j + \beta_k)z$$
$$+\cos(\omega_i - \omega_j - \omega_k)t - (\beta_i - \beta_j - \beta_k)z$$

The nonlinear susceptibility of the optical fiber generates new waves at the angular frequencies $\omega_r \pm \omega_s \pm \omega_t (r, s, t = 1, 2 \dots)$. Equation 4.3 represents the effects of SPM and XPM. Terms in equation 4.3 can be neglected, due to lack of phase matching. The remaining terms can satisfy the phase matching condition.

FWM is a phenomenon that occurs in the case of DWDM systems in which the wavelength channel spacing are very close to each other. This effect is generated by the third order distortion that creates third order harmonics. As shown in Figure 1, these cross products interfere with the original wavelength and cause the mixing. In fact, these spurious signals fall right on the original wavelength which results in difficulty in filtering them out. In case of 3 channel system, there will be 9 cross products, where 3 of them will be on the original wavelength. This is caused by the channel spacing and fiber dispersion. If the channel spacing is too close, then FWM occurs. If the dispersion is lesser, then FWM is higher since dispersion is inversely proportional to mixing efficiency.

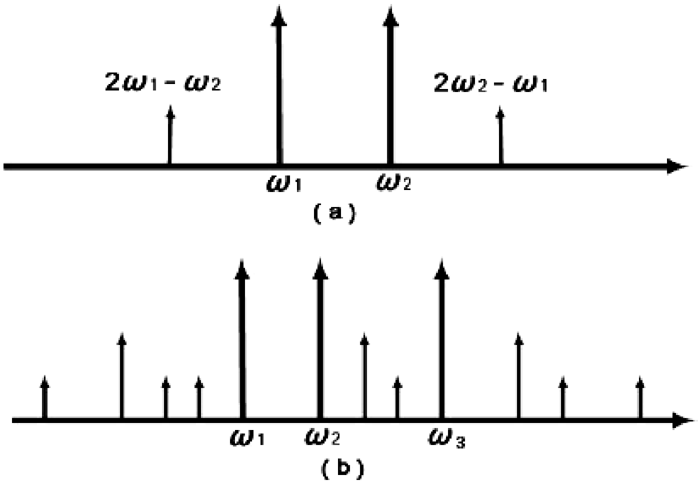

Figure 1: (a) two input signals ω_1 and ω_2 (b) three input signals ω_1, ω_2 and ω_3 and the arising new frequency components due to FWM

It can be seen that three of the interfering products fall right on top of the original three signals and the remaining six products fall outside of the original three signals. These six wavelengths can be optically filtered out. The three interfering products that fall on top of the original signals are mixed together and cannot be removed by any means. Figure 1 shows results graphically. The three tall solid bars are the three original signals. The shorter cross-ched bars represent the nine interfering products. The number of the interfering products increases as $(N3\text{-}N2)\ /2$where N is the number of signals.

III. RESULT AND DISCUSSION

We have simulated an experimental setup for analysis of FWM phenomenon. The peak power is launched into the fiber is approx 6W, while the power of the signal was 2.4 mW as shown in Figure 2. In order to compare the performance of the optical fibers numerical experiment setup has proposed, we applied the same parameters and conditions for the six types of fibers including the influence of the gain and received power of the induced fiber. At the output of the system, the FWM process between the pump and the signal in any specific optical fiber gave gain and its performance at received signal power for a particular length of fiber.

The block diagram of commercial optical fibers with spectral analyzer has shown in Figure 2. All commercial fibers have different parameters gives FWM based wavelength conversion

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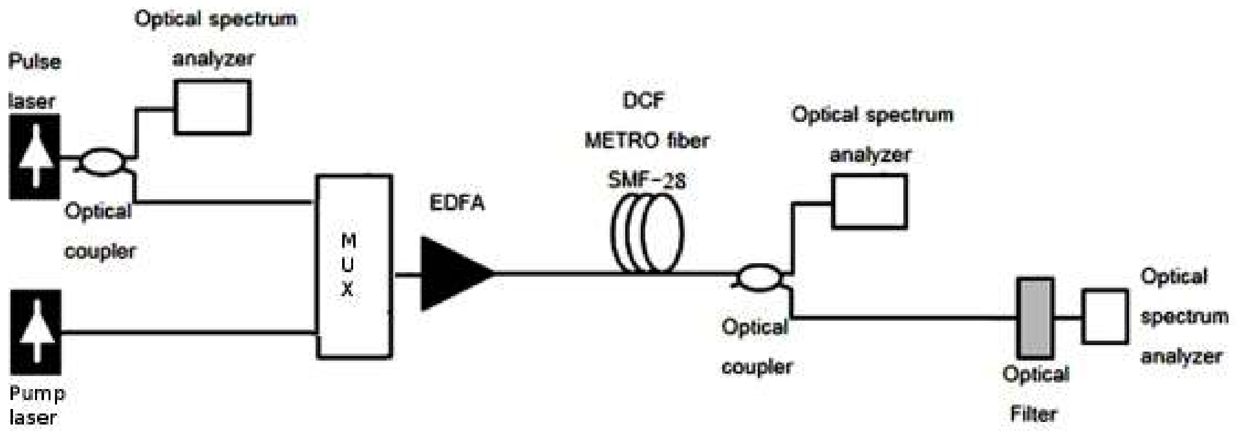

Figure 2: Block Diagram of FWM analysis in commercial optical fibers

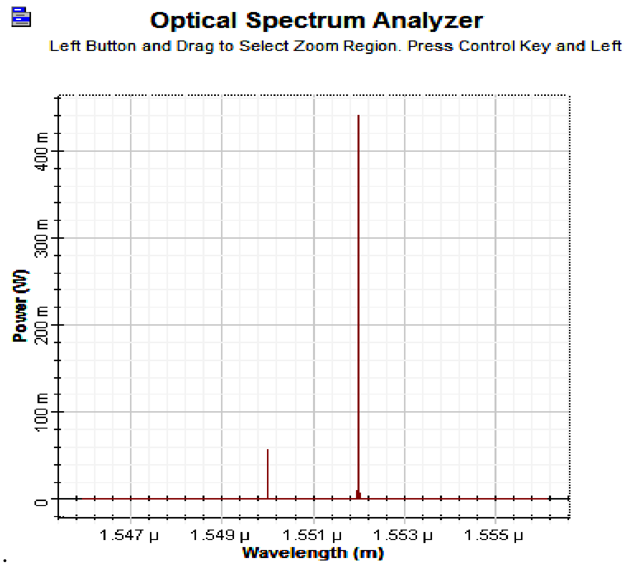

Figure 3(a): Spectral analysis obtained at the input (W) of the SMF-28 fiber

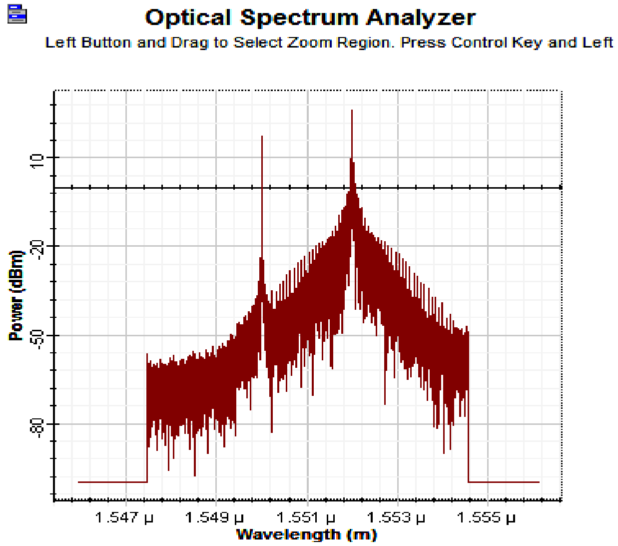

Figure 3(b): Spectral analysis obtained at the output of the SMF-28optical fiber

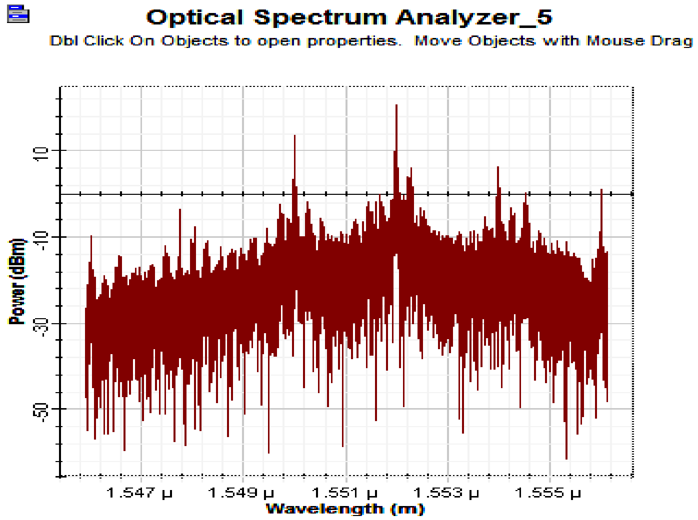

Figure 3(c): Spectral analysis obtained at the output (W) of the SMF-28 optical fiber

Spectral analyses at output of MTRO fiber has shown below in fig.4 and compare it with fig.3(c).

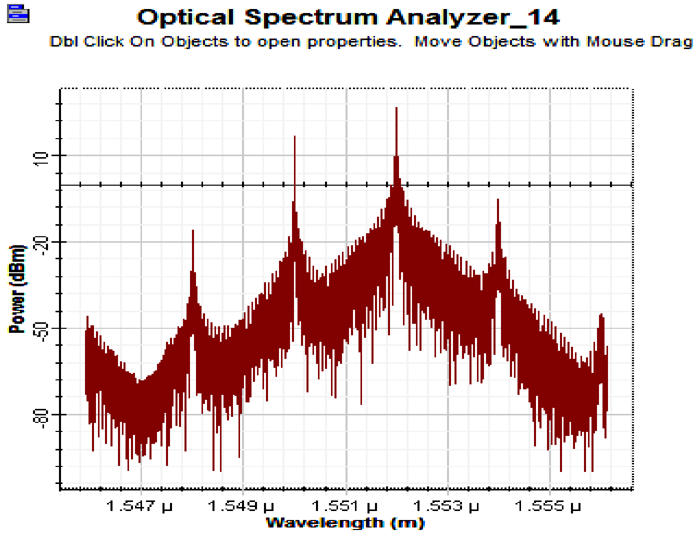

Figure 4: Spectral analysis obtained at the METRO optical fiber.

BER and eye diagram of single mode fiber at receiving end has shown in figure 5.

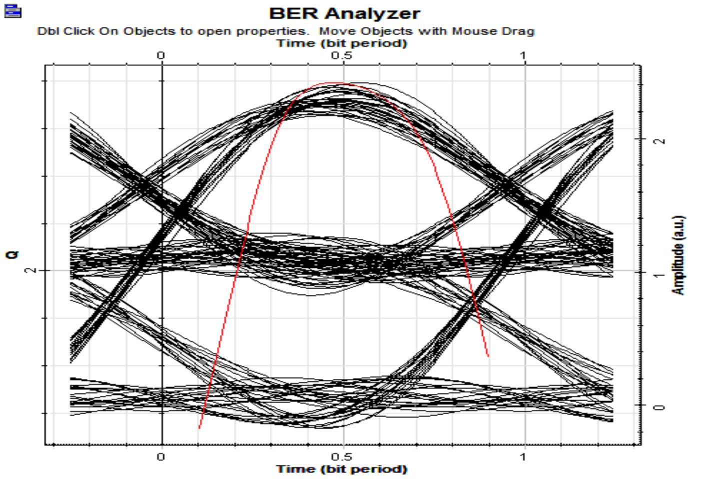

Figure 5: BER and Eye diagram obtained at the output SMF-28 optical fiber

Table 1: Comparison of Gain obtained in various applied commercial fibers

Types of Fiber	Received power At 1 km		
	Wavelength(nm)	Gain(db)	Output signal(dbm)
SMF	1552	-14.53	15.1963
	1550	-4.3276	13.3846
DCF	1552	-0.748	29.0451
	1550	-1.88	15.8215
LEAF	1552	-0.4813	29.2477
	1550	-0.6496	17.0626
PMD	1552	-0.7504	28.9787
	1550	-1.0841	16.6281
VASCADE	1552	-0.5100	29.2091
	1550	-0.8170	16.8952
METRO	1552	-0.2535	29.4755
	1550	-0.6794	17.0328

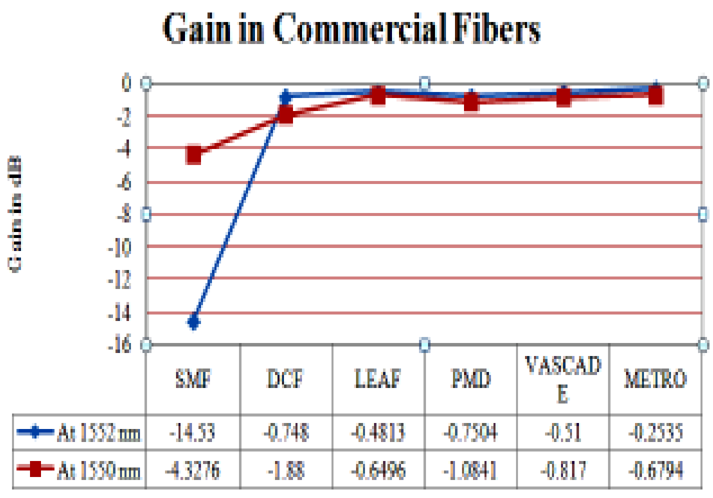

Figure 6: Comparison of gain in commercial optical fibers

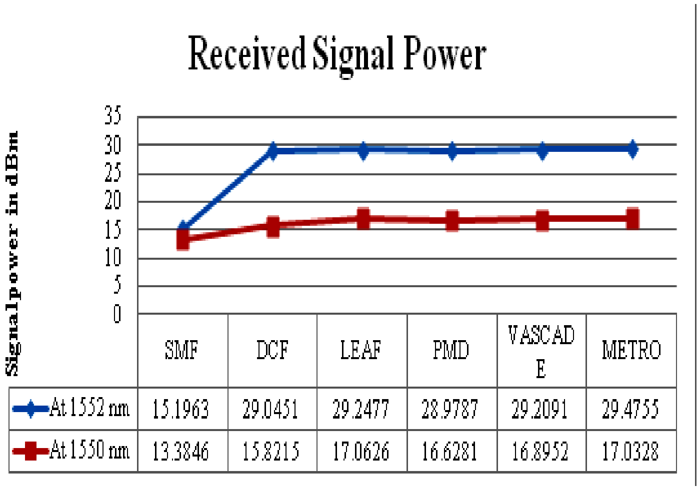

Figure 7 Received signal power for commercial optical fibers

It is observed in figure 6 that gain in SMF is lower than METRO optical fiber, but increasing the effective area that reduces the Four Wave Mixing effect and brings improvement in gain and received signal power in all commercial optical fibers as indicated in Table 1.

All results obtained indicate that, the FWM effects depend on dispersion and effective area of optical fiber. This is because the longer optical fiber, the more light interacts with the fiber material and the greater the nonlinear effects. We also have noticed that, the behavior of the DCF fiber has the highest peak power compared to the SMF-28 optical fiber. This was due to the relative advantage of the DCF fiber characteristics compared to SMF optical fibers.

In other types of fibers, when changing the effective area, it is observed that gain of signal is improved and output power is also improved.

IV. CONCLUSION

In the paper, it is shown as to how the nonlinearity in the commercial optical fiber has been utilized for wavelength conversion. The performance of the commercial optical fiber in FWM based wavelength conversion covering the entire C-band has been analyzed.

In the simulated WDM system, high pump power transmitted signals were used. It was observed that as high power transmission of WDM signal, maximum nonlinear effect is occurred within the various commercial optical fibers. Bit Error Rate was measured by Eye Diagram for the performance measurement besides gain and received signal power. Performance evaluation of the simulated system revealed that the METRO fiber has better performance for the transmission of WDM signals in comparison with SMF, DCF, LEAF and VASCADE and found to be more useful for FWM based wavelength conversions.

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