FOUR-WAVE-MIXING BASED WAVELENGTH CONVERSION USING DIFFERENT TYPES OF FIBERS

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Abstract

We demonstrate four-wave-mixing (FWM) based wavelength conversion at 1.55 µm using four different types of optical fibers. For a pump peak power of ~6 W, 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 and for different fiber lengths.

Keywords: Four-Wave-Mixing (FWM); optical fiber communication; nonlinear optics; wavelength conversion.

1. 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 [1]. In optical communication systems the term nonlinearity refers to the dependence of the system on power of the optical beam/s 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 multiwavelength systems together with optical amplifiers creates major nonlinear effects such as stimulated raman scattering (SRS), stimulated brillioun scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave-mixing (FWM) [2]. These effects have proven to of utility in a great number of applications including pulse compression, solitons, optical tunable delays, optical switching, pulse retiming and wavelength conversion [3].

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 [4]. 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 [4-5]. Several all-optical wavelength conversion approaches have been demonstrated, which are based on nonlinearities in semiconductor optical amplifiers [6], in optical fibers [7-8], in crystals [9] and so on. Among these approaches, wavelength conversion based on the nonlinearity of optical fibers is inherently featured of femtosecond response time, low insertion loss, non-degraded extinction radio of the signal and low-noise characteristics [10], 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 [11]. 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 [12]. However to make use of this nonlinear phenomenon in optical signal processing requires that a suitable fiber be available. So far, a FWM-based wavelength converter has been demonstrated by using a fabricated W-type soft glass fiber [13] or using a highly nonlinear photonic crystal fiber [14] or using a highly nonlinear holey fiber [15].

In this paper, we have embarked to the authors' knowledge for the first time four different commercial optical fibers to achieve a wavelength conversion covering the entire C-band and make a comparison in their performance using a numerical simulation. The numerical simulating software is Optisystem 7.0 from Optiwave Inc.. The remainder of this paper is organized as follows. The mathematical review is presented in Section 2. Based on the theory presented, a numerical analysis of the wavelength conversion process is carried out in Section 3.This is followed by the main conclusion in Section 4.

2. Mathematical Review

2.1. *Nonlinear phenomena*

When a light signal of high power impinges on an optical fiber, the refractive index changes in accordance with the power of the signal. The refractive index *n* may be expressed as

$$n=n_0+n_2 I \qquad (1)$$

where:

n_o is the linear refractive index
n_2 is the nonlinear refractive index, and
I is the power density of the signal

As a result of this, a variety of nonlinear phenomena occur in the optical fiber, including SPM, XPM, FWM, Brillouin scattering, and so on [16].
In a linear medium, the electric polarization P is assumed to be a linear function of the electric field E:

$$P=\varepsilon_0 \chi E \qquad (2)$$

where for simplicity a scalar relation has been written. The quantity χ is termed as linear dielectric susceptibility. At high optical intensities (which corresponds to high electric fields), all media behave in a nonlinear fashion. Thus Eq. (2) gets modified to

$$P=\varepsilon_0(\chi E+\chi^{(2)}E^2+\chi^{(3)}E^3+\ldots) \qquad (3)$$

where $\chi^{(2)}$, $\chi^{(3)}$, … are higher order susceptibilities giving rise to the nonlinear terms. The second term on the right hand side is responsible for second harmonic generation, sum and difference frequency generation, parametric interactions etc. while the third term is responsible for third harmonic generation, intensity dependent refractive index, self-phase modulation, four wave mixing etc. For media possessing inversion symmetry $\chi^{(2)}$ is zero and there is no second order nonlinear effect. Thus silica optical fibers, which form the heart of today's communication networks, do not possess second order nonlinearity [17].

2.2. *Theory of FWM*

The origin of FWM process lies in the nonlinear response of bound electrons of a material to an applied optical field. In fact, in order to understand the FWM effect, consider a WDM signal, which is sum of *n* monochromatic plane waves. The electric field of such signal can be written as

$$E = \sum_{p=1}^{n} E_p \cos(w_p t - k_p z) \qquad (4)$$

Then the nonlinear polarization is given by

$$P_{nl} = \varepsilon_o \chi^{(3)} E^3 \qquad (5)$$

For this case P_{nl} takes the form as

$$P_{nl} = \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} \sum_{q=1}^{n} \sum_{r=1}^{n} E_p \cos(w_p t - k_p z) E_q \cos(w_q t - t_q z) E_r \cos(w_r t - k_r z) \qquad (6)$$

Expansion of above expression gives,

$$\begin{aligned} P_{nl} = {} & \frac{3}{4} \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} (E_p^2 + 2\sum_{q \neq p} E_p E_q) E_p \cos(w_p t - k_p z) \\ & + \frac{1}{4} \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} E_p^3 \cos(3w_p t - 3k_p z) \\ & + \frac{3}{4} \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} \sum_{q \neq p} E_p^2 E_q \cos\{(2w_p - w_q)t - (2k_p - k_q)z\} \\ & + \frac{3}{4} \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} \sum_{q \neq 1} E_p^2 E_q \cos\{(2w_p + w_q)t - (2k_p + k_q)z\} \\ & + \frac{6}{4} \varepsilon_o \chi^{(3)} \sum_{p=1}^{n} \sum_{q > p} \sum_{r > q} E_p E_q E_r \{\cos((w_p + w_q + w_r)t - (k_p + k_q + k_r)z) \\ & + \cos((w_p + w_q - w_r)t - (k_p + k_q - k_r)z) \\ & + \cos((w_p - w_q + w_r)t - (k_p - k_q + k_r)z) \\ & + \cos((w_p - w_q - w_r)t - (k_p - k_q - k_r)z)\} \qquad (7) \end{aligned}$$

The first terms in above equation represents the effect of SPM and XPM. Second, third and fourth terms can be neglected because of phase mismatch. The reason behind this phase mismatch is that, in real fibers k(3ω) ≠ 3k(ω) so any difference like (3ω −3k) is called as phase mismatch. The phase mismatch can also be understood as the mismatch in phase between different signals traveling within the fiber at different group velocities. All these waves can be neglected because they contribute little. The last term represents phenomenon of four-wave mixing [3].

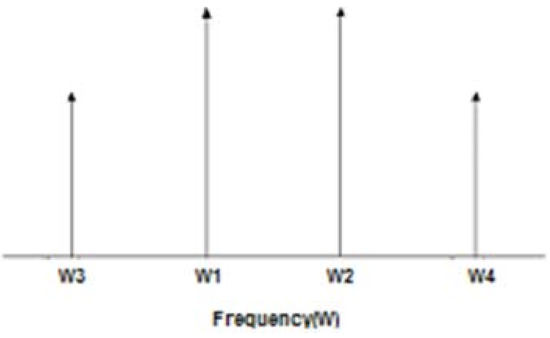

Fig.1. FWM of two wave ω1and ω2

Figure 1 shows a simple example of mixing of two waves at frequency ω1 and ω2. When these waves mixed up, they generate sidebands at ω3 and ω4 such that (ω1+ ω2=ω3+ω4) [18]. Similarly, three copropagating waves will create nine new optical sideband waves at frequencies given by Eq. (8). These sidebands travel along with original waves and will grow at the expense of signal-strength depletion.

In general for ***N*** wavelengths launched into fiber, the number of generated mixed products ***M*** is,

$$M = (N^2/2)(N-1) \qquad (8)$$

3. Numerical Results and Discussion

Four-wave-mixing phenomenon can be used effectively for wavelength conversion by using a phenomenological method as shown in fig.2 [3].

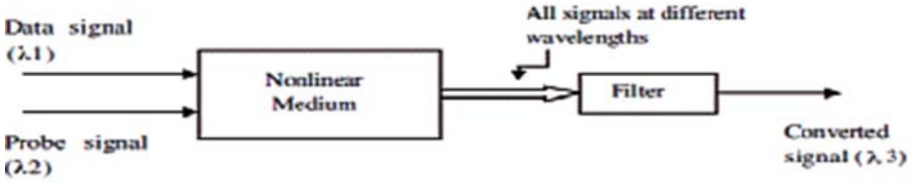

Fig.2.Phenomical description of wavelength conversion through FWM

The numerical setup for the FWM-based wavelength converter is shown in Fig.3.

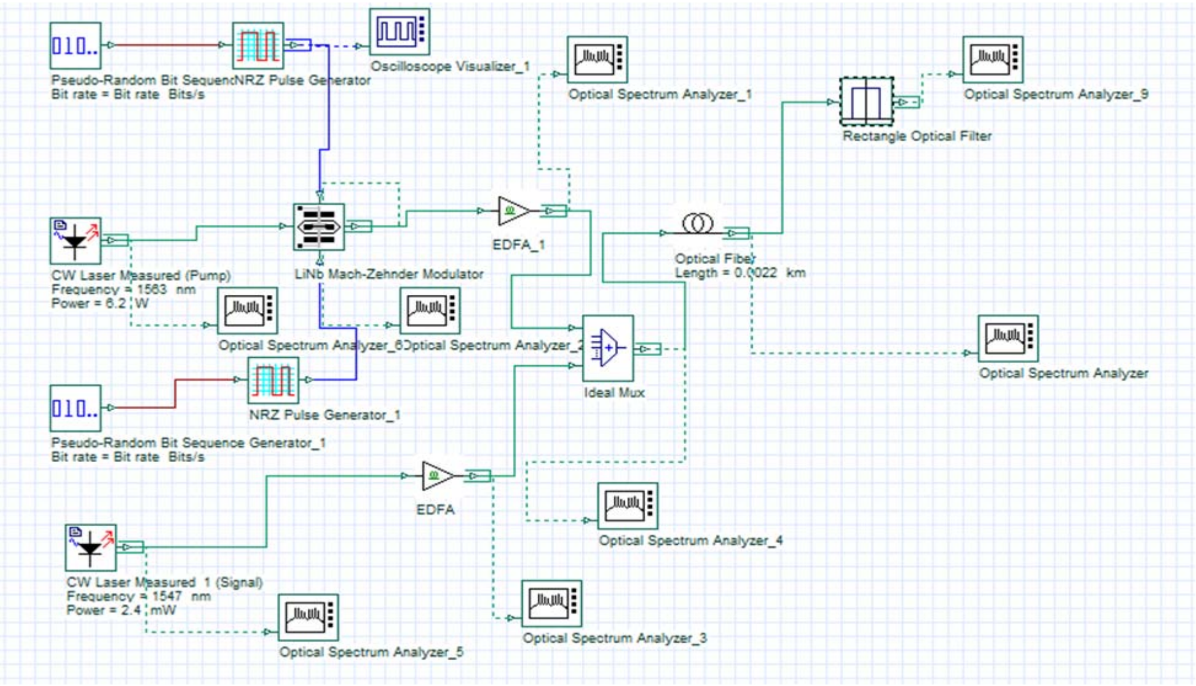

Fig.3.The numerical setup for the FWM-based wavelength converter

The converter was based on four different commercial optical fibers which are: SMF-28 single mode fiber, positive dispersion non-zero dispersion-shifted fiber (LEAF), negative dispersion non-zero dispersion-shifted fiber (METRO) and dispersion compensating fiber (DCF).We initially used the same parameters as in [12] for the pump power, signal power and fiber length. Two continuous-wave (CW) lasers, tuned inside the C-band, were used as the pump and signal sources. In order to achieve peak pump powers of the order of a few Watts with a moderate average-power fiber amplifier, the pump was modulated using a $LiNbO_3$ Mach-Zehnder modulator with rectangular pulses. The modulated pump and the CW signal beams were amplified by two separate fiber amplifiers and combined through an ideal multiplexer.

This configuration allowed us to independently control the power of the two beams, and also ensured that nonlinear interaction of the two signals occurred only in the applied fiber. The peak power of the pump into the fiber was 6.2 W, while the power of the signal was 2.4 mW. In order to compare the performance of the wavelength conversion numerical experiment, we will apply the same parameters and conditions for the four types of fibers including the influence of the length 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 rise to a clear wavelength converted beam as shown in fig. 4 (a) for the DCF optical fiber of 2.2m length and also in fig.4 (b) for the same optical fiber of 22m length.

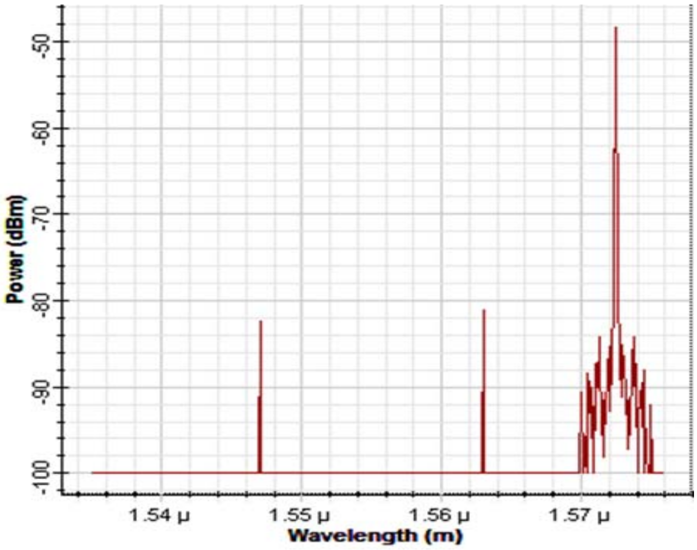

Fig.4. (a) Spectral analysis obtained at the output of the 2.2m DCF fiber

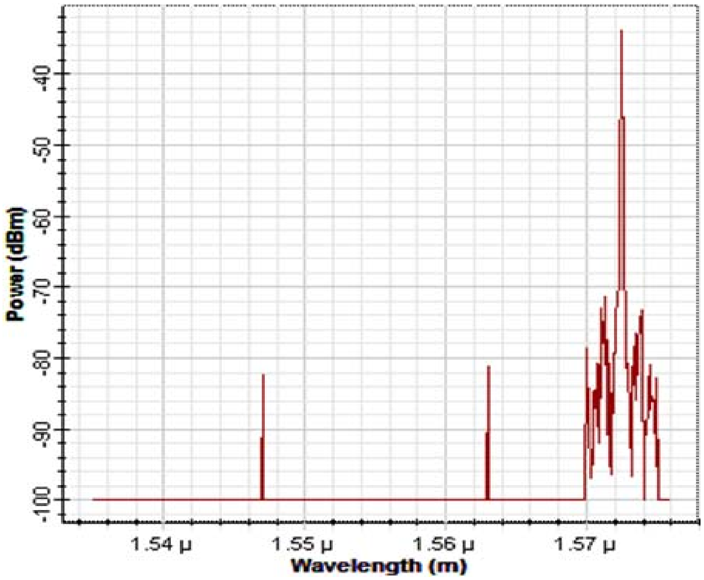

Fig.4. (b) Spectral analysis obtained at the output of the 22m DCF fiber

We have repeated the same procedure for the other three types of optical fibers and we have observed the same behavior but with different optical converted signal peak power. The obtained results are summarized and compared in Table 1.

Table.1. Comparison between the applied commercial fiber and the effect of the fiber length

Type of Optical Fiber	**Received Peak Optical Power in dBm at 1572.48nm**	
	2.2m fiber length	**22m fiber length**
Dispersion Compensating Fiber (DCF)	-48.279	-33.7538
Single Mode Fiber SMF-28	-56.05208	-40.07226
Positive Dispersion Non-zero Dispersion-Shifted Fiber (LEAF)	-55.47787	-45.2033
Negative Dispersion Non-Zero Dispersion-Shifted Fiber (METRO)	-57.60205	-48.4033

All results obtained indicate that, the nonlinear effects depend on the transmission length of the optical fiber. This is because the longer the optical fiber, the more the light interacts with the fiber material and the greater the nonlinear effects. On the other hand, we have noticed that, the behavior of the DCF fiber has the highest peak power compared to the other three types of fibers even when changing the fiber length. This was due to the relative advantage of the DCF fiber characteristics compared to the other optical fibers.

4. Conclusion

In this paper, the performance of four different commercial optical fibers in a FWM-based wavelength conversion covering the entire C-band has been numerically analyzed. The results show that, the DCF optical fiber has been shown to be a good candidate for wavelength conversion compared to the other commercial fibers. On the other hand, simulations revealed that, by increasing fiber length from 2.2m to 22m for all types of fibers, the performance obtained from the system increase.

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