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Self-Phase Modulation Based Wavelength Conversion using Different Types of Fibers

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Abstract

We demonstrate Self-Phase Modulation (SPM) based wavelength conversion at 1.55 µm using three different commercial types of optical fibers. A numerical simulation is used to predict the performance of each type of fibers and to address the potential of each fiber type in wavelength conversion applications utilizing self-phase modulation. It is shown that a wavelength conversion over ± 5 nm can be achieved with around 30 mW output peak signal power leading to a remarkable better performance.

Keywords: Self-Phase Modulation (SPM), 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 multi-wavelength 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, provides 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. Among the various nonlinear phenomena exploited for fiber-based wavelength conversion, SPM is regarded to be one of useful applied technique to achieve a wavelength converter with a potential of high conversion efficiency, wide conversion bandwidth, ultrafast response time and low insertion loss [11]. However to make use of this nonlinear phenomenon in optical signal processing requires that a suitable fiber be available. So far, a SPM-based wavelength converter has been demonstrated by using a highly nonlinear microstructure fiber [12] or using a highly nonlinear photonic crystal fiber [11].

In this paper, we have embarked to the authors' knowledge for the first time three different commercial optical fibers to achieve a wavelength conversion covering over ± 5 nm 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

$$n = n_0 + n_2 I \tag{1}$$

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 [13].

In a linear medium, the electric polarization P is assumed to be a linear function of the electric field E:

$$P = \varepsilon_o \chi E \tag{2}$$

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 equation (2) gets modified to

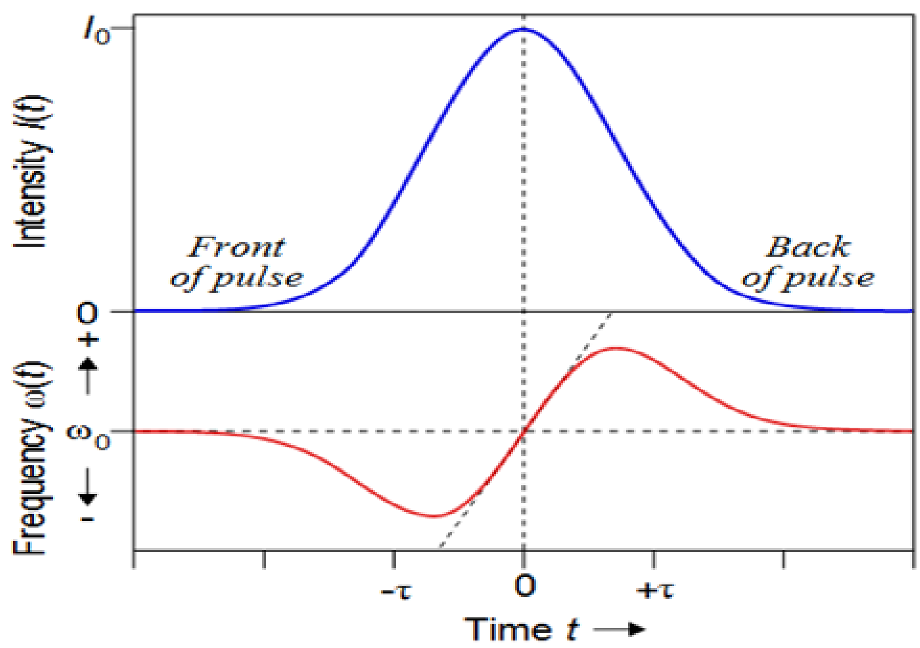
$$P = \varepsilon_0(\chi E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots) \tag{3}$$

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 [14].

2.2. Theory of SPM

Self-phase modulation is a nonlinear optical effect of light-matter interaction [15]. An ultra-short pulse of light, when traveling in a medium, will induce a varying refractive index of the medium due to the optical Kerr effect. This variation in refractive index will produce a phase shift in the time domain. Therefore, the intensity profile of the pulse does not change only the spectrum of the pulse changes. As shown in Fig.1 [15], a pulse (top curve) propagating through a nonlinear medium undergoes a self-frequency shift (bottom curve) due to self-phase modulation. The front of the pulse is shifted to lower frequencies, the back to higher frequencies. In the center of the pulse, the frequency shift is approximately linear.

Figure 1: Frequency shift due to SPM



When an optical pulse is transmitted through an optical fiber, the Kerr effect causes a time-dependent phase shift according to the time-dependent pulse intensity. So SPM modulates the phase of the pulse by an amount proportional to the instantaneous pulse intensity [16, 17].

The spectral broadening can be represented as [18]

$$\Delta\omega = -\frac{2\pi n_2 L}{\lambda A_{eff}} \frac{dP(t)}{dt} \tag{4}$$

where $\Delta\omega$ is the frequency chirp, L is the distance traveled, λ is the wavelength of the pulse, A_{eff} is the effective core area of the fiber, and P(t) is the optical power.

The relation of the frequency chirp $\Delta\omega$ and wavelength width $\Delta\lambda$ can be represented as

$$\Delta\omega = -(2\pi c/\lambda^2)\Delta\lambda \tag{5}$$

So, the spectral broadening can also be written as

$$\Delta\lambda = \frac{n_2 L\lambda}{cA_{eff}}\frac{dP(t)}{dt} \quad (6)$$

Therefore, SPM can be utilized to induce spectral broadening for achieving wavelength conversion.

The fiber nonlinearity is determined by the nonlinear susceptibility of the fiber glass and the effective core area of the guided mode. It is described by the nonlinear coefficient γ as

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (7)$$

From equations (4) and (7), the spectral broadening owing to SPM can be represented in a simple format as

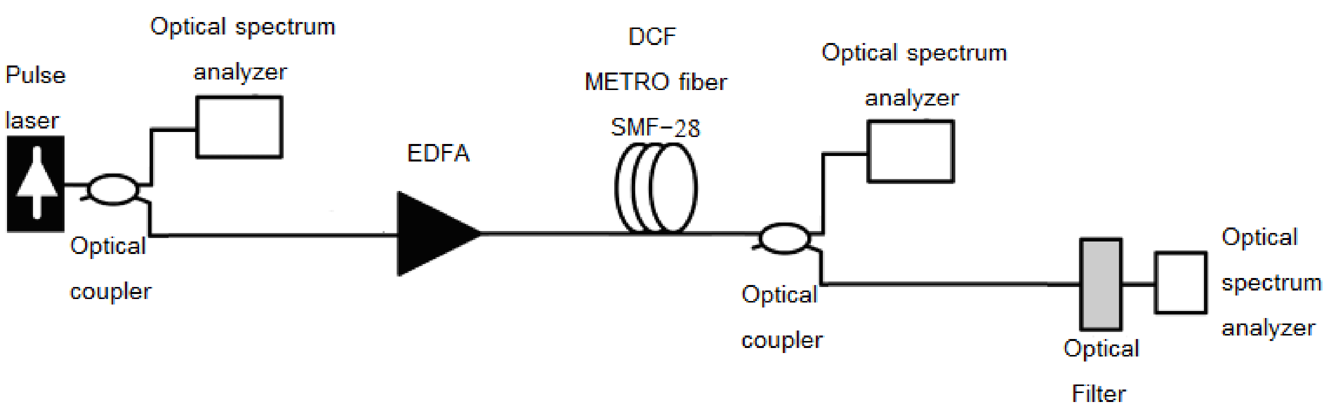
$$\Delta\omega = (-\gamma L)\frac{dP(t)}{dt} \quad (8)$$

The degree of spectral broadening will enhance if the nonlinear coefficient γ increases. From equation (8), in order to strong spectral broadening, we have four alternatives: using a highly nonlinear optical fiber or embedding a high optical input power or by means of an optical fiber with a large length or using one or more of the previous approaches.

3. Numerical Results and Discussion

The wavelength conversion system based on SPM is illustrated in Fig.2. The converter was based on three different commercial optical fibers which are: SMF-28 single mode fiber, negative dispersion non-zero dispersion-shifted fiber (METRO) and dispersion compensating fiber (DCF). The basic scheme of the SPM-based wavelength converter consists of a high gain erbium-doped fiber amplifier (EDFA), a specific commercial optical fiber and a tunable optical filter. The input signal with pulse width 45 ps with 1550 nm central wavelength is amplified by the EDFA. Then, the amplified laser pulse is send into a particular type of fiber. The spectrum of the signal is broadened due to SPM. The tunable optical filter is utilized at the output port to filter out the converted signal from the broadened spectrum.

Figure 2: Wavelength conversion system based on SPM



As the key part of the SPM-based wavelength converter, the selected optical fiber seems very important for achieving effective SPM. From equation (7), there are two approaches to enhance the fiber nonlinearity for the strong spectral broadening. The first one is to use a new glass material with a high nonlinear refractive index. The second available approach is to use a fiber with a very small core effective area. However, we used three widely deployed commercial fibers where each has its own nonlinear coefficient. But as a nonlinear medium in the wavelength converters experiment, traditional silica fiber provides low Kerr nonlinearity. Therefore, we will embed a tunable booster EDFA with high optical gain (up to 45 dB). Thus, the applied amplifiers will enhance the optical power of the signal in order to increase the degree of spectral broadening to compensate the high core effective area of the applied traditional optical fibers in order to achieve a wavelength converter with a good behavior as shown in our results.

The peak power of the signal is set to 2.4 mW as in [19] and the fiber length of 100 m is used as in [12]. In order to compare the performance of the wavelength conversion numerical experiment, we will apply the same parameters and conditions for the three types of fibers including the influence of the gain of the amplifier and the length of the induced fiber. Fig.3 shows the spectrum of the input light pulse induced in all the fiber types. Fig.4 shows the spectrum broadening effect due to SPM from the DCF fiber of 100 m length with maximum gain of EDFA (45 dB). At the output of the system, a wavelength conversion is achieved with a good efficiency as shown in Fig.5 with a tunable optical filter with central wavelength of 1555 nm. The power peak is located at 1555 nm.

Figure 3: Spectrum of the input signal

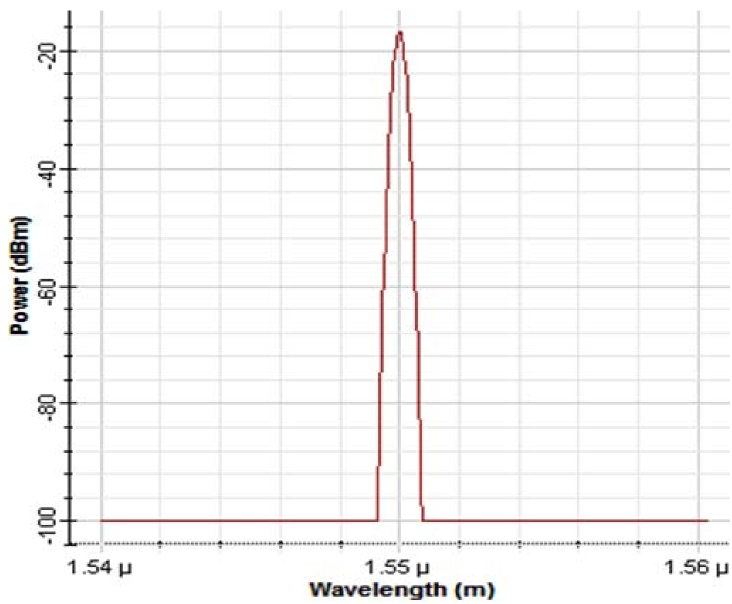


Figure 4: Broadening effect obtained due to SPM in DCF fiber of 100 m length with EDFA gain of 45 dB

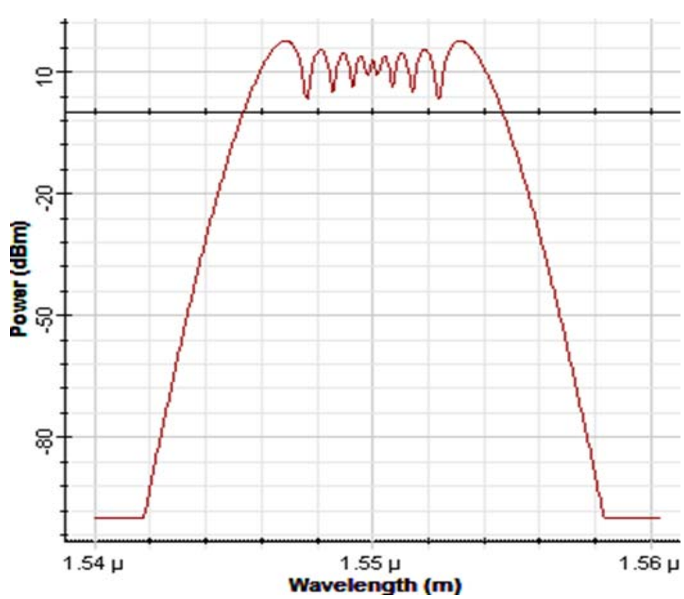
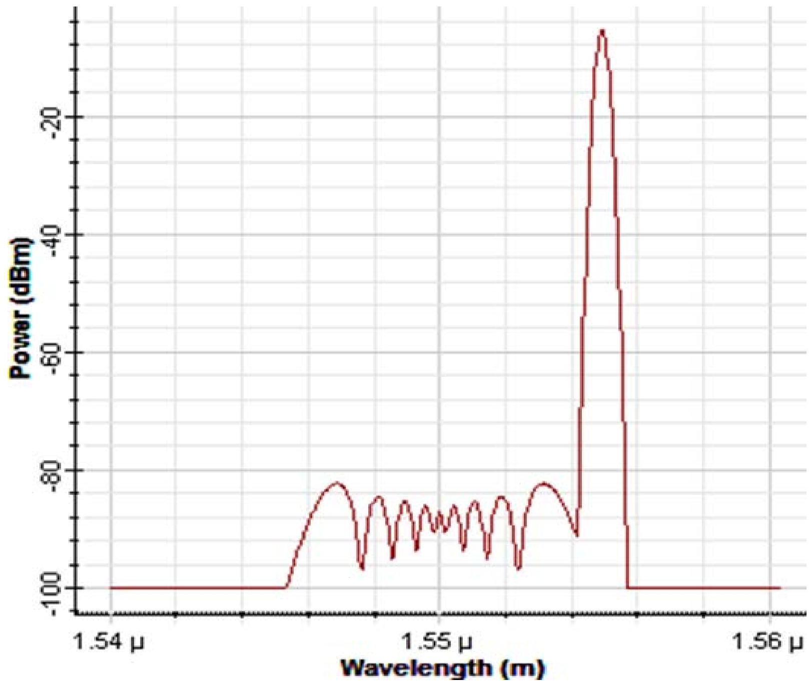


Figure 5: Converted spectrum obtained after the filter with central wavelength of 1555 nm



We have repeated the same procedure for the other two types of optical fibers and three different EDFA gain levels. We have observed the same behavior but with different range of spectral broadening using a threshold power (0 dBm) for the wavelength conversion process. This threshold was chosen to give the ability to compare between the three commercial fibers in their broadening behavior. The obtained results are summarized and compared in table 1.

Table 1: Comparison between the applied commercial fiber and the effect of the EDFA gain

Type of Optical Fiber	Spectral Broadening at 0 dBm in nm		
	35 dB EDFA gain	40 dB EDFA gain	45dB EDFA gain
Dispersion Compensating Fiber (DCF)	±0.78	±1.82	± 4.71
Single Mode Fiber SMF-28	±0.57	±1.05	±2.38
Negative Dispersion Non-Zero Dispersion-Shifted Fiber (METRO)	±0.53	±0.97	±2.1

We have noticed that the behavior of the DCF fiber has the highest spectral broadening compared to the other two types of fibers even when changing EDFA gain level. This was because to the relative advantage of the DCF fiber characteristics compared to the other optical fibers especially it has the smallest core effective area leading to the highest nonlinear coefficient among the applied fibers [20].

On the other hand, the initial optical pulse waveform from the pulse generator with wavelength of 1550 nm is illustrated in Fig. 6. The converted pulse with wavelength of 1555 nm based on the DCF fiber in the wavelength conversion process is shown in Fig.7. It can be deduced that the wavelength conversion from 1550 nm to 1555 nm is achieved with a remarkable efficiency. We have achieved a gain range of around 13 times the initial optical pulse and a conversion range of ± 5 nm due to the symmetry of the spectrum broadening effect of the SPM instead of around twice the initial optical pulse and a conversion range of ± 4 nm in [12]. A negligible time delay is induced in the output converted optical pulse waveform as in [12].

Figure 6: Initial optical pulse from the pulse generator with central wavelength of 1550 nm

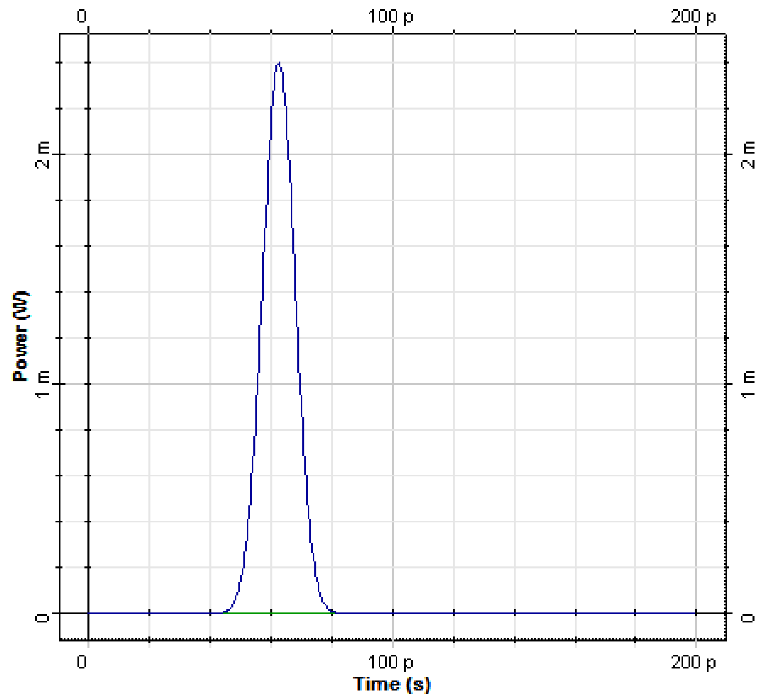
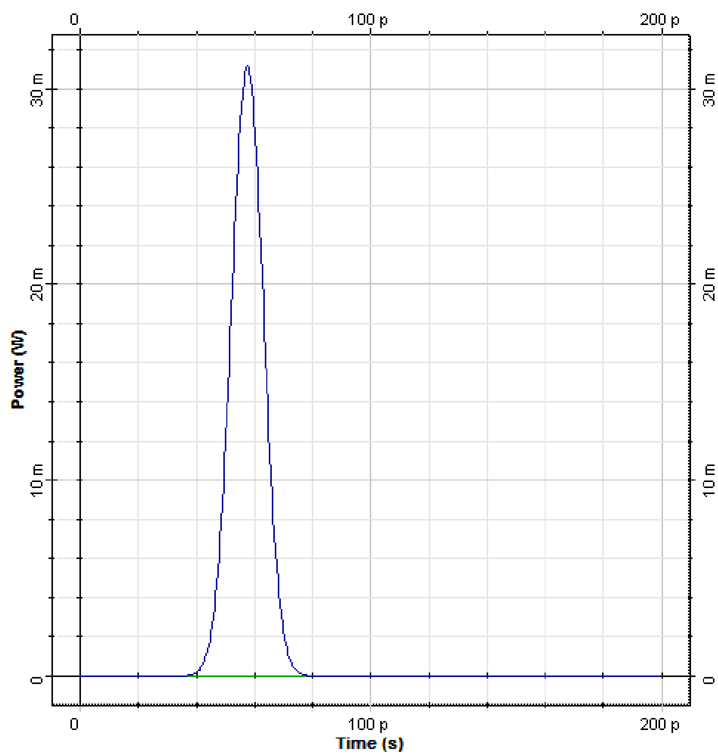
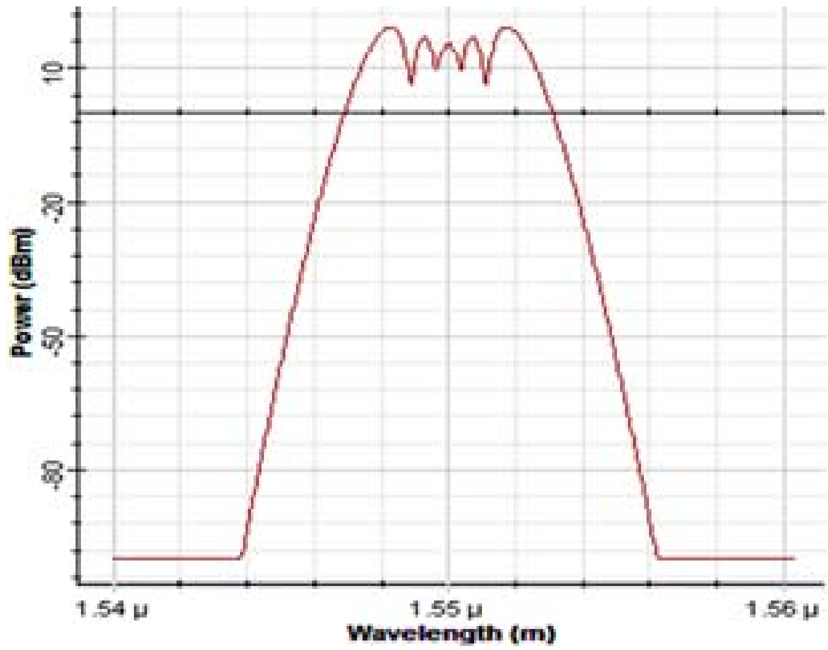


Figure 7: Converted optical pulse after the optical filter with central wavelength of 1555 nm



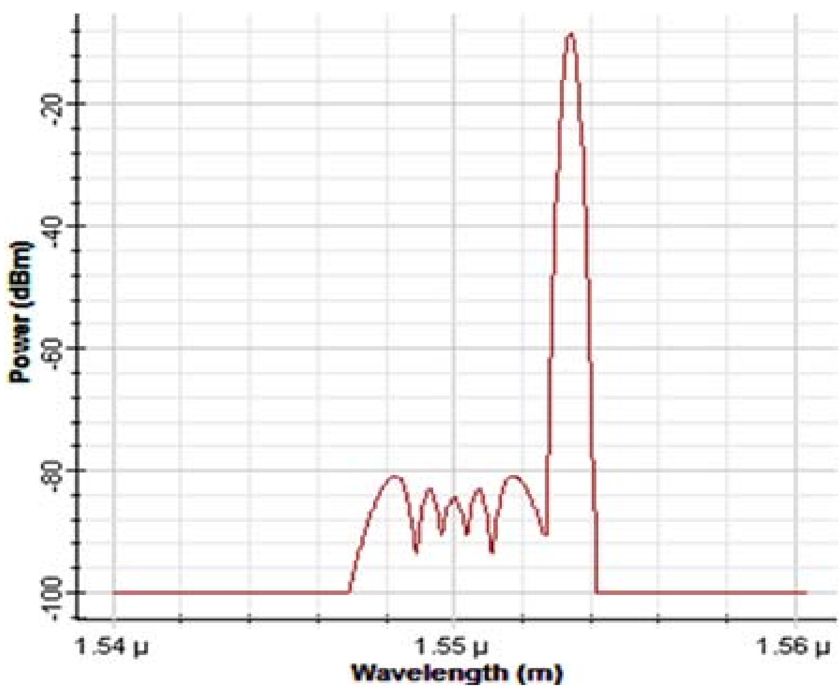
Besides of the previous results, we have analyzed the influence of the length of the applied optical fiber. However, in order to compare its impact we will fix the EDFA gain to 45 dB for all types of fibers. Fig.8 shows the spectrum broadening effect due to SPM from the DCF fiber of 60m length.

Figure 8: Broadening effect obtained due to SPM in DCF fiber of 60 m length with EDFA gain of 45 dB



At the output of the system, a wavelength conversion is achieved with a good efficiency as shown in Fig.9 with a tunable optical filter with central wavelength of 1553.5 nm. The power peak is located at 1553.5 nm.

Figure 9: Converted spectrum obtained after the filter with central wavelength of 1553.5 nm



We have repeated the same procedure for the other two types of optical fibers and with two different optical fiber lengths. We have observed the same behavior but with different range of spectral broadening using a threshold power (0 dBm) for the wavelength conversion process. The obtained results are summarized and compared in table 2.

Table 2: Comparison between the applied commercial fiber and the effect of the fiber length

Type of Optical Fiber	Spectral Broadening at 0 dBm in nm	
	20 m fiber length	60 m fiber length
Dispersion Compensating Fiber (DCF)	±1.45	±3.1
Single Mode Fiber SMF-28	±0.92	±1.65
Negative Dispersion Non-Zero Dispersion-Shifted Fiber (METRO)	±0.85	±1.48

All results obtained indicate that, the nonlinear effect (SPM broadening effect) 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. This entire outcomes match with equation (8). On the other hand, we have noticed that the behavior of the DCF fiber has the highest spectral broadening compared to the other two types of fibers even when changing the fiber length.

4. Conclusion

In this paper, the performance of three different commercial optical fibers in a SPM-based wavelength conversion 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 and other related researches using specially manufactured nonlinear mediums. On the other hand, simulations revealed that, by increasing EDFA gain level and/or fiber length for all types of fibers, the performance obtained from the wavelength conversion process enhance.

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