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Research Article

Broadband Enhancement of Optical Frequency Comb Using Cascaded Four-Wave Mixing in Photonic Crystal Fiber

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A cascaded intensity modulator (IM) and phase modulator (PM) are used to modulate a continuous-wave (CW) laser and generate an optical frequency comb (OFC). Thus, the generated comb is utilized as an initial seed and combined with another CW-laser to generate four-wave mixing (FWM) in photonic crystal fiber (PCF). Results show that an initial flat 30 GHz OFC of 29, 55 lines within power fluctuation of 0.8 dB and 2 dB, respectively, can be achieved by setting the ratio of the DC bias to amplitude of sinusoidal signal at 0.1 and setting the modulation indices of both IM and PM at 10. Moreover, the 1st order of FWM created through 14 m of PCF has over 68 and 94 lines with fluctuation of 0.8 dB and 2 dB, respectively. Hence, the generated wavelengths of 1st left and right order of FWM can be tuned in a range from ~1500 nm to ~1525 nm and ~1590 nm to ~1604 nm, respectively.

1. Introduction

Generation of four-wave mixing (FWM) in highly nonlinear low-dispersion fibers was intensively studied, so it can be utilized as an optical source for wavelength-division multiplexing (WDM) system [1–4]. Basically only two wavelengths are needed to cause the interaction between each other in nonlinear fiber to induce a nonlinear phase modulation at the beat frequency. Hence new sidebands (i.e., FWM) can be generated on both sides of the main wavelengths. Moreover, as the new lines propagate along the fiber, interaction of the lines with each other occurred, and then cascaded FWM is created. An optical feedback to the input port scheme was proposed to enhance the cascaded four-wave mixing (CFWM) generation [5]. To generate frequency comb within broad bandwidth over highly nonlinear fiber (HNLF), the absolute value of the HNLF dispersion should not exceed 1 ps/nm/km within the comb range. In 2003, Okuno et al. have successfully fabricated flattened-HNLF with properties that satisfied the simplified dispersive requirement; unfortunately it failed to generate continuous-wave- (CW-) seeded frequency comb [6]. In 2012, Myslivets et al. successfully managed to generate broadband optical frequency combs based on cascaded FWM in highly nonlinear fiber low-power, continuous-wave seeds, but the flatness is too poor [7]. High sensitivity in highly nonlinear fiber (HNLF) was achieved when the signal's wavelength is positioned at the band edge of the modulation instability (MI) spectrum generated by an intense degenerate four-wave mixing (FWM) pump [8]. In 2008, an investigation was conducted by using conventional fibers and ultraflattened dispersion photonic crystal fibers to generate 118 FWM products over bandwidth of 300 nm [2]. In 2009, an optimized technique using three-pumps with unequally spaced frequencies was implemented to generate frequency combs by four-wave mixing in highly nonlinear low-dispersion fibers [3]. Zhang et al. used highly nonlinear photonic crystal fiber (PCF) to generate wavelength-tunable optical pulse train based on four-wave mixing [1]. An alternative configuration based on nonlinear effect of intensity and phase modulators was implemented to generate OFC [9–11]. Unfortunately, using configuration with small number of phase modulators led to either poor flatness over large bandwidth or a limited number of lines over small flat bandwidth, the only way to achieve wide flat bandwidth by cascading many modulators, which is very expensive. Therefore, in 2014 a very simple configuration consists of intensity and phase modulators, two lasers sources and highly nonlinear fiber, was investigated and showed that the modulators sidebands

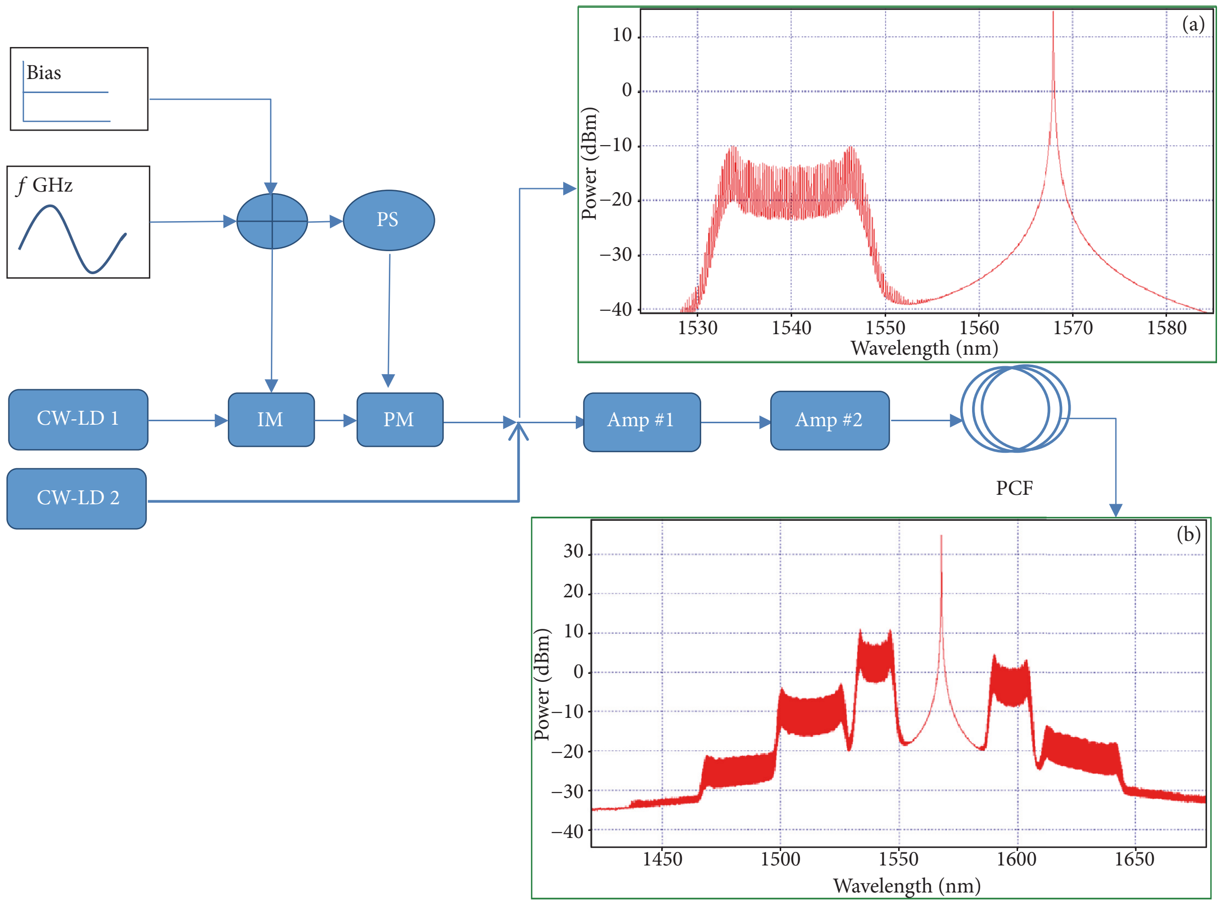

Figure 1: Configuration of optical frequency combs (CW-LD1, 2: continuous wave laser sources, IM: intensity modulator, PM: phase modulator, PS: phase shift, Amp: optical amplifier, and PCF: photonic crystal fiber).

were doubled after the highly nonlinear fiber and over 100 lines were achieved [12, 13]. In terms of application, optical frequency comb is very useful for high-repetition-rate pulse train generation [14] and for injection locking of widely separated lasers [15]. Such OFC can reduce the cost of WDM system, where many wavelengths can be generated and each can be used to carry single user's data [16]. In addition, by using an appropriate optical bandpass filters to select certain sidebands from OFC comb and beating any two wavelengths in photodetector will generate millimeter-wave signal that can be used for 5G application [17].

Hence, in this paper, with advantages of nonlinear optics effect of intensity modulator (IM) followed by phase modulator (PM) and FWM caused by two laser sources over 14 m of photonic crystal fiber cascaded four-wave mixing was achieved. Furthermore, the spacing between the two laser sources and nonlinear coefficient of PCF were investigated to choose the optimum values to increase the bandwidth of the FWM as compared to the initial comb generated by a cascade of IM and PM.

2. System Setup

Figure 1 shows the configuration of the optical frequency comb, which consists of a cascade of one intensity modulator followed by one phase modulator. Both of the modulators were driven by a sinusoidal signal with a frequency of 30 GHz, which modulated a continuous-wave (CW) laser wavelength centered at 1540 nm. Then, the output combined with another laser source centered at wavelength 1568 nm. Both laser sources are set at 15 dBm. Hence, the initial comb was generated as shown in inset (a), Figure 1. A cascade of two optical amplifiers were added to increase the power of the generated lines. Then, the initial comb passes through 14 m of photonic crystal fiber (PCF), which helps to generate more lines in terms of FWM as shown in inset (b), Figure 1. I set PCF parameters as in [18], which has the following parameters: linear losses = 0.2 dB/km, group velocity dispersion D = 0.2 ps/nm/km, slope S = 0.001 ps/nm^2/km, and nonlinear coefficient $C = 10\,\mathrm{W}^{-1}\,\mathrm{km}^{-1}$.

3. System Evaluation

Using the same parameters mentioned in [11], the configuration managed to create 29, 55 lines within power fluctuation of 0.8 dB and 2 dB, respectively, as PM output spectrum as shown in inset (a), Figure 1. The generated spectrum was utilized as an initial comb, which is amplified by two optical amplifiers, so all the lines will have almost the same power

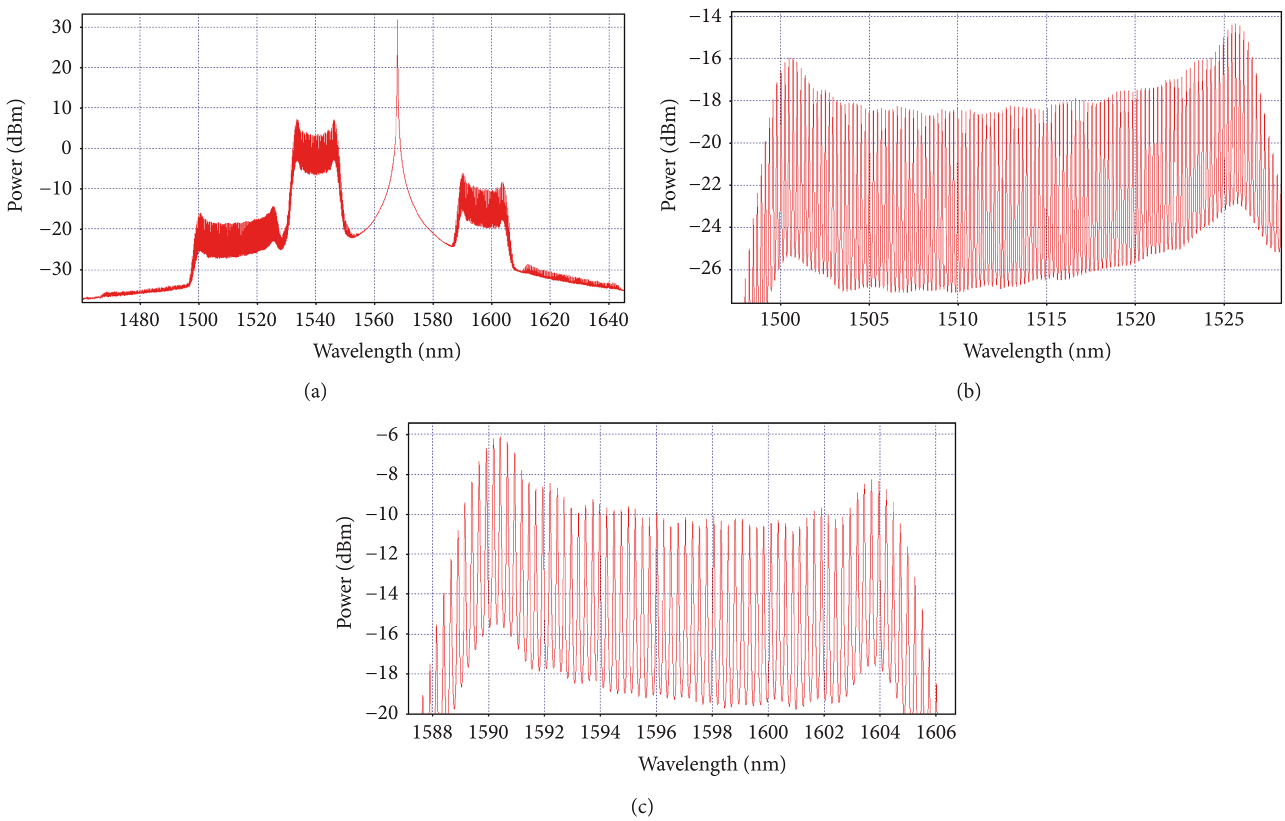

FIGURE 2: (a) Output spectrum of PCF. Zoomed-in view of FWM (b) left order and (c) right order.

equal to 32 dBm. Then it passes in 14 m of PCF with properties mentioned in Section 2. Clearly, as it is shown in Figure 2, the system was able to generate few orders of FWM. According to [12], the first left order of FWM centered at frequency $2f_1 - f_2 = 1512$ nm and the first right order of FWM centered at frequency $2f_2 - f_1 = 1596$ nm, where f_1 and f_2 are the center frequencies of lasers 1 and 2. It is notable that the left FWM has more lines as compared to the right orders, where first left order has 68 and 94 lines with power fluctuation of 0.8 dB and 2 dB, respectively, and the first right order has 21 and 42 lines with power fluctuation of 0.8 dB and 2 dB, respectively. This indicated that the generated FWM has wider bandwidth as compared to the initial comb generated by a cascade of IM and PM.

The system also was simulated at different optical amplifiers power, in other words, different input power to PCF, and it was found that as the power increases more lines are generated as shown in Figure 3. Basically, to generate FWM, the phase matching should be conserved, and this can be achieved when the wave vector mismatch $k = \Delta k + \Delta k_{NL} = 0$, where Δk and Δk_{NL} represent the wave vectors mismatch related to dispersion and nonlinear effects, respectively. $\Delta k_{NL} = C(P_1 + P_2)$, where P_1 and P_2 are the incident power of laser sources #1 and #2, respectively [4]. Therefore, by adjusting Δk_{NL}, phase matching condition can be achieved, and hence FWM occurred. Moreover, the generated FWM can interact with each other, and then more FWM can be generated as shown in Figure 3. Subsequently, Figure 4 shows average number of lines, left and right separately.

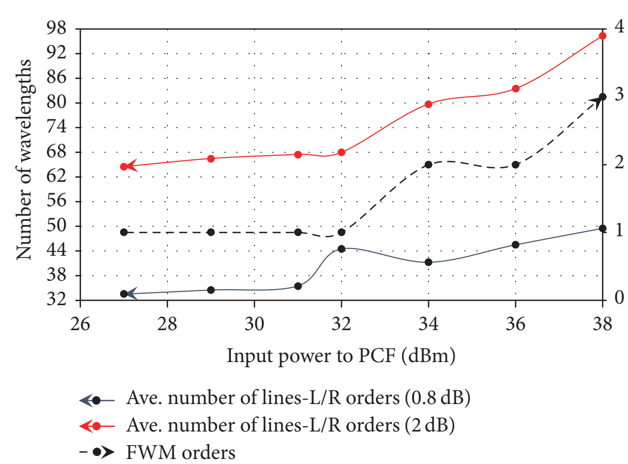

FIGURE 3: Number of generated wavelengths versus input power to PCF.

Furthermore, spacing between the two laser sources should be chosen carefully in order to increase the number of lines as shown in Figure 5. It was found that FWM order bandwidth increases as the spacing between the laser sources increases. In addition, the FWM order will be totally

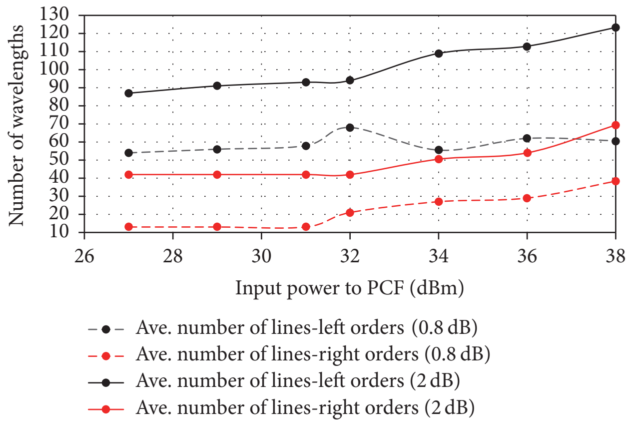

FIGURE 4: Number of generated wavelengths (left and right orders separately) versus input power to PCF.

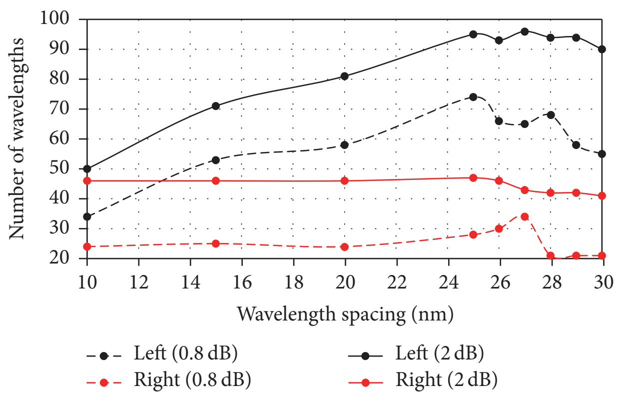

FIGURE 5: Number of wavelengths versus CW-LDs wavelengths spacing.

separated from the initial comb when the spacing is around 28 nm. Unfortunately any further increment will affect the number of lines per FWM order. In conclusion, by tuning the second laser source within this range, then broadened FWM combs can be achieved.

The system also was simulated at different values of nonlinear coefficient of PCF, and it was found that as the input power to PCF was maintained at 32 dBm, only one order was created when nonlinear coefficient (C) is between 6 and 12 $\mathrm{W^{-1}\,km^{-1}}$, and two orders were created when $C \geq 14\ \mathrm{W^{-1}\,km^{-1}}$. Hence, as the nonlinear coefficient increases more orders of FWM could be generated, subsequently more lines created as shown in Figure 6, which shows the average number of lines for the right and left FWM orders versus nonlinear coefficient. Subsequently, Figure 7 shows average number of lines, left and right separately. Clearly more lines can be achieved even at low nonlinear coefficient and low power.

4. Conclusion

In conclusion, this paper presents a simple configuration consisting of two stages, the first stage generates an initial

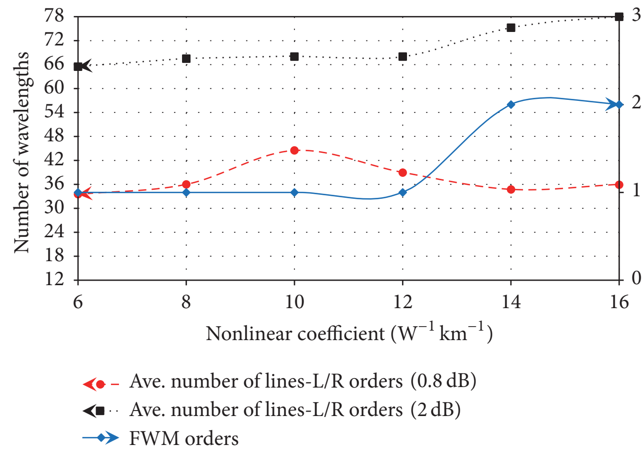

FIGURE 6: Number of generated wavelengths versus nonlinear coefficient.

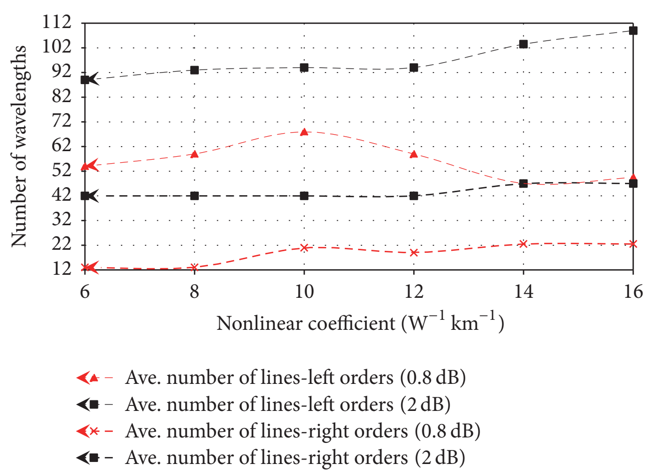

FIGURE 7: Number of generated wavelengths (left and right orders separately) versus nonlinear coefficient.

comb using a cascade of intensity and phase modulators. Then, this initial comb is combined with another laser and passed through PCF to cause FWM. Moreover, by controlling the spacing between the laser sources and the nonlinear coefficient of PCF, FWM bandwidth and number of orders can be controlled. Finally, number of lines of the 1st order of FWM increases by 134% and 71% of the initial comb within power fluctuation of 0.8 dB and 2 dB, respectively.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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