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Broad optical bandwidth based on nonlinear effect of intensity and phase modulators through intense four-wave mixing in photonic crystal fiber

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Abstract. This work investigates the advantages of nonlinear optics of a cascaded intensity modulator (IM) and phase modulator (PM) to generate an initial optical frequency comb. The results show that when the direct current bias to amplitude ratio, $\alpha = 0.1$, and the IM and PM have the same modulation index and are equal 10, seed comb is achieved; it is generated by the modulation of two continuous wave lasers. Hence, based on these parameters, an intense four-wave mixing is created through 9 m of photonic crystal fiber. Moreover, a broadband spectrum was achieved, spaced by a 30-GHz microwave frequency. [DOI: 10.1117/1.OE.56.5.056111]

Keywords: four-wave mixing; intensity modulators; phase modulator; nonlinear optics; photonic crystal fiber.

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1 Introduction

Over the past 30 years, various methods have been reported on broadband multiwavelength light sources, and most of these methods are based on erbium-doped fiber (EDF). However, this kind of laser source suffers from instability output due to the homogeneous line broadening of the EDF at room temperature. Therefore, adding frequency shifter[1] or phase modulator (PM)[2] is considered an alternative method. In addition, nonlinear optics such as Brillouin[3] and four-wave mixing (FWM)[4] are also used to generate new wavelengths. FWM occurs when two or more wavelengths are transmitted simultaneously over the same medium; in this case, the dependence of the refractive index not only causes phase shift within the channel but also gives rise to signals at new frequencies. Investigation was implemented on cascaded four-wave mixing (CFWM) and self-phase modulation (SPM) processes in nonlinear effects in highly nonlinear fiber (HNLF).[5] The paper recorded 103 lines when SPM occurs and 43 lines when CFWM and SPM occur. On the other hand, Zhang et al. implemented a simple configuration to generate a wavelength-tunable optical pulse train based on FWM in highly nonlinear photonic crystal fiber (PCF).[4] In 2008, additional investigation was conducted on CFWM based on 2.5 m of PCF, and experimental results showed that 118 FWM lines were generated.[6] Other configurations consist of a cascade of the intensity modulator (IM) and PM being implemented, and results showed that an optical frequency combs (OFC) can be easily achieved.[7–9] Unfortunately, multiwavelength sources based on the nonlinear effect of the IM and PM provide either poor flatness over the bandwidth of interest or a limited number of sidebands over which flatness can be maintained. The bandwidth can be increased by cascading many modulators, which is very expensive. Therefore, in Ref. 10, two laser sources were used to generate FWM along with the PM and IM and broadband was achieved through the advantages of cascaded FWM. Furthermore, in 2014, a very simple configuration consisting of only the IM and PM, two laser sources, and HNLF was investigated and showed that the modulators sidebands doubled after the HNLF and over 100 lines were achieved.[11]

Hence, in this paper, with the advantage of the nonlinear optics effect of both FWM caused by the two laser sources over a 9-m photonics crystal fiber and a cascade of the IM followed by the PM, broad optical bandwidth was achieved, and parameters such as direct current (DC) bias, amplitude of the sinusoidal waveform, and phase modulator's voltage were investigated. Furthermore, the spacing between the two laser sources was chosen carefully to achieve the broad optical bandwidth.

2 System Setup

The configuration of the OFC system setup, which is shown in Fig. 1, consists of a cascade of one IM followed by one-phase modulators, and both of the modulators are driven by a sinusoidal source with a frequency of 30 GHz, which modulated a continuous wave (CW) laser wavelength centered at 1555 nm and passed through the IM and the output of the IM combined with another laser source centered at wavelength 1532 nm and passed through the PM. Both laser sources are set at 22 dBm. Hence, the initial comb was generated, as shown in Fig. 1 (inset A). A cascade of optical amplifiers was added to increase the power of the generated lines. Then, the initial comb passed through 9-m PCF, which helped to generate an intense FWM, as shown in Fig. 1 (inset B). I set PCF parameters as in Ref. 12, which has the following parameters: linear losses = 0.2 dB/km, group velocity dispersion $D = 1$ ps/nm/km, slope $S = 0.001$ ps/nm^2/km, effective area $A_{\mathrm{eff}} = 80$ μm^2, and nonlinear coefficient $C = 12$ W^{-1} km^{-1}. The advantages of using a short length of PCF depend on the moderate phase mismatch; by keeping the product $\Delta\beta L$ small, where L is the fiber length and $\Delta\beta$ is the linear phase mismatch, $\Delta\beta = \beta(\omega_4) + \beta(\omega_3) - \beta(\omega_1) - \beta(\omega_2)$, where $\beta(\omega_i)$ is the waveguide propagation constant at frequency ω.

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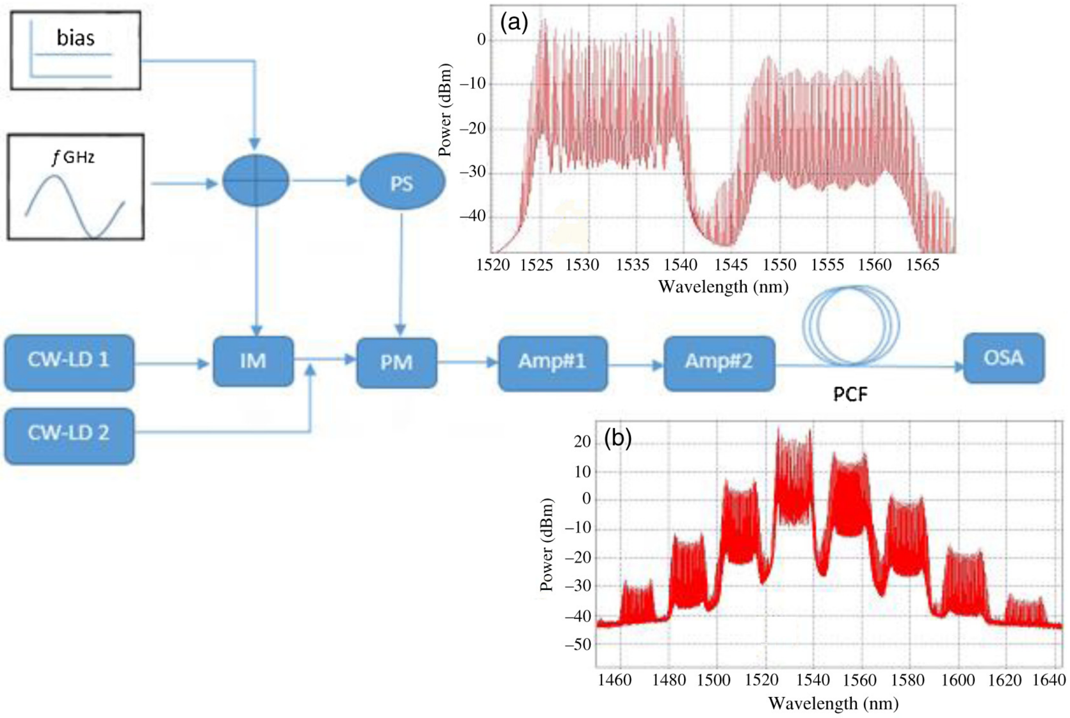

Fig. 1 Configuration of optical frequency combs (CW-LD1, 2, continuous wave-laser sources; IM, intensity modulator; PM, phase modulator; PS, phase shift; Amp, optical amplifier; PCF, photonic crystal fiber).

3 System Evaluation

Recently, I simulated a simple configuration to generate multiwavelength lasing based on the nonlinear effect of a cascaded IM and PM.[13] In the mentioned configuration, I chose carefully the optimum value of DC bias/amplitude ratio ($\alpha = 0.1$) and (DC bias/amplitude) to phase modulator's voltage ratio (i.e., $\gamma = \alpha/V\pi = 0.1$), and I managed to achieve 51 lines with a power fluctuation 1.5 dB and

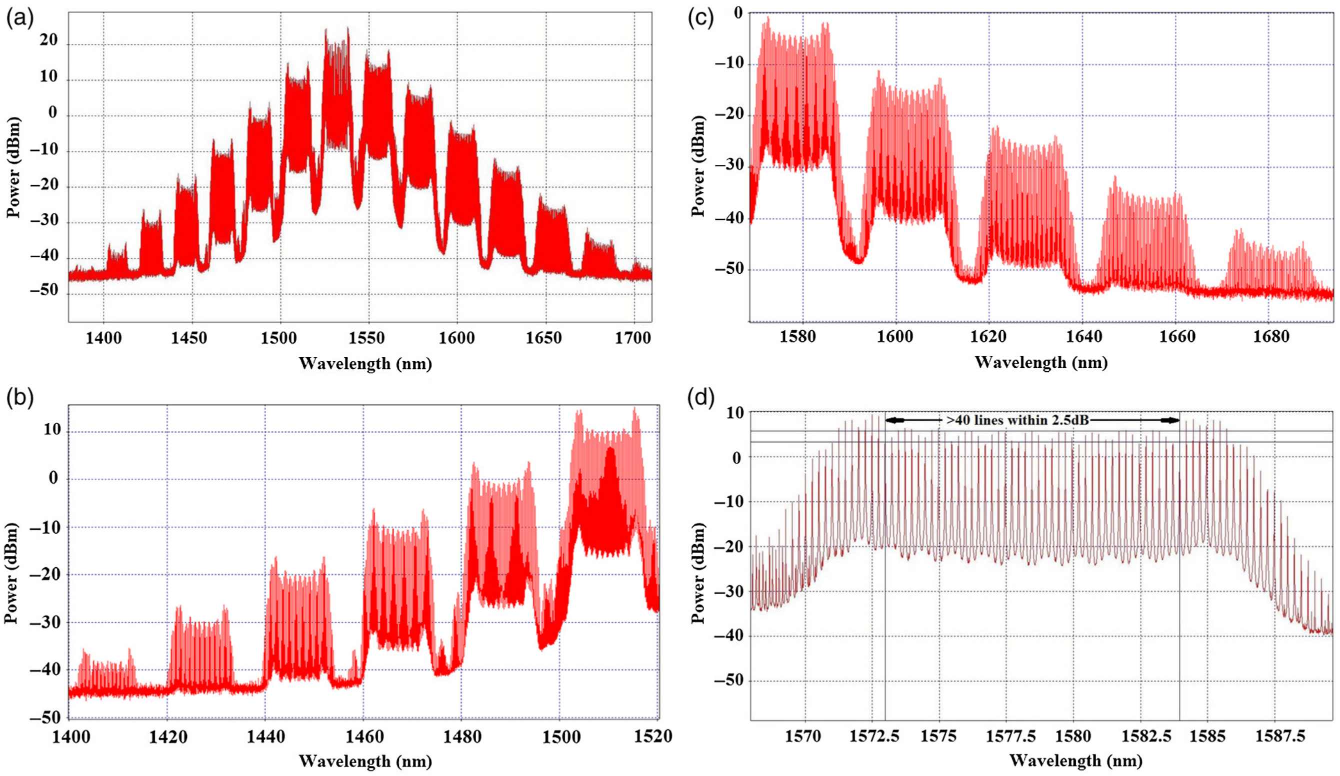

Fig. 2 (a) Output spectrum of PCF; zoomed-in view of FWM, (b) left orders, (c) right orders, and (d) first order.

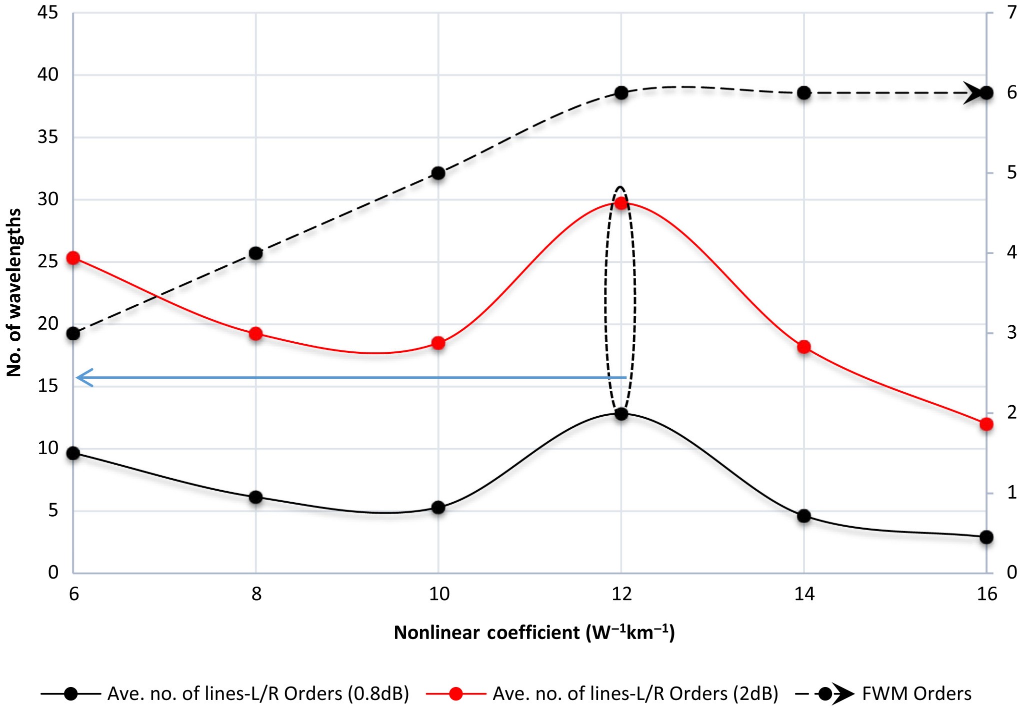

Fig. 3 Number of generated wavelengths versus nonlinear coefficient.

63 lines within 3.7 dB.[13] Therefore, using these parameters in this paper, the simulation results, inset A in Fig. 1, show that the seed combs centered at 1532 and 1555 nm, which feed into PCF with the properties mentioned in Sec. 2. Hence, the system was capable of creating six-orders of FWM; on average, each has 12 and 29 lines with power fluctuations of 0.8 and 2 dB, respectively, spaced by 30 GHz. The zoom-in view of the FWM spectrum with six-orders on the left and five-orders on the right seed combs are shown in Figs. 2(b) and 2(c). Thus, in total, the system comprised about 132 and 319 lines with power fluctuations of 0.8 and 2 dB, respectively. Figure 2(d) shows a zoomed-in view of the first-order of FWM, which has over 40 lines with a power fluctuation of 2.5 dB. According to the study reported in Refs. 10 and 11, the right n'th-order of FWM is centered at frequency $(N+1)f_1 - Nf_2$, and the left n'th-order of FWM is centered at frequency $(N+1)f_2 - f_1$, where f_1 and f_2 are the center frequencies of laser 1 and 2, respectively.

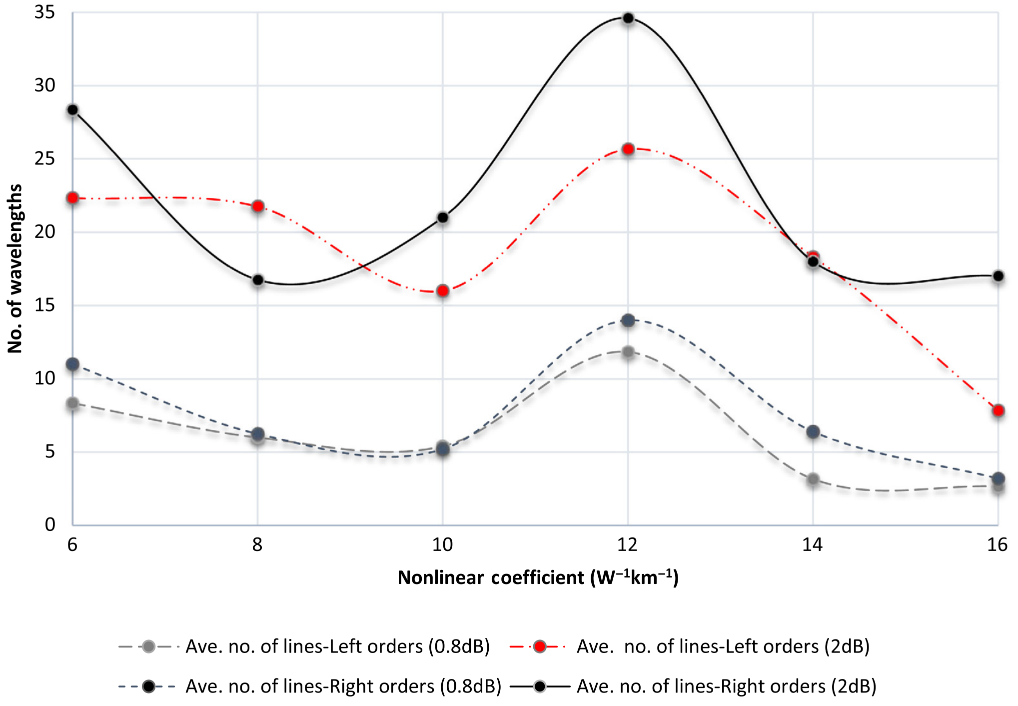

Fig. 4 Number of generated wavelengths (left and right orders separately) versus nonlinear coefficient.

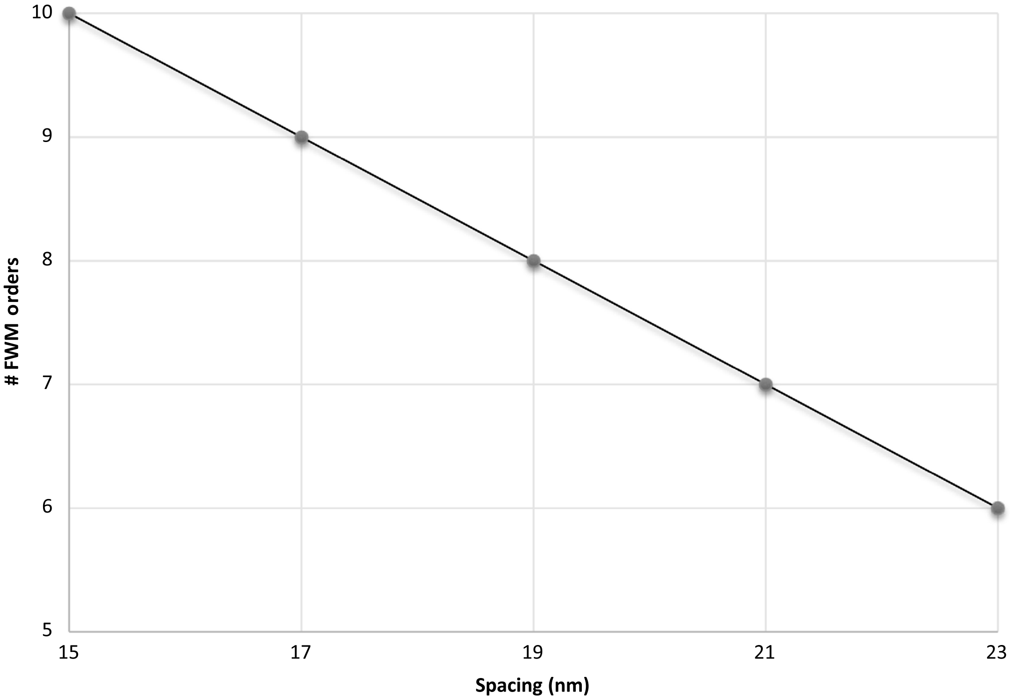

Fig. 5 Number of FWM orders versus CW-LDs wavelengths spacing.

The system also simulated at different values of the nonlinear coefficient of PCF, and it was found that only three-orders were created when the nonlinear coefficient $C = 6\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, four orders when $C = 8\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, and six-orders when $C \geq 12\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. Hence, as the nonlinear coefficient increases, more orders of FWM could be generated, and, subsequently, more lines could be created, as shown in Fig. 3. Figure 4 shows the average number of wavelengths for the right and left FWM orders versus the nonlinear coefficient. Clearly from Figs. 3 and 4, the maximum number of generated lines occurred when the nonlinear coefficient was $12\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. 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.

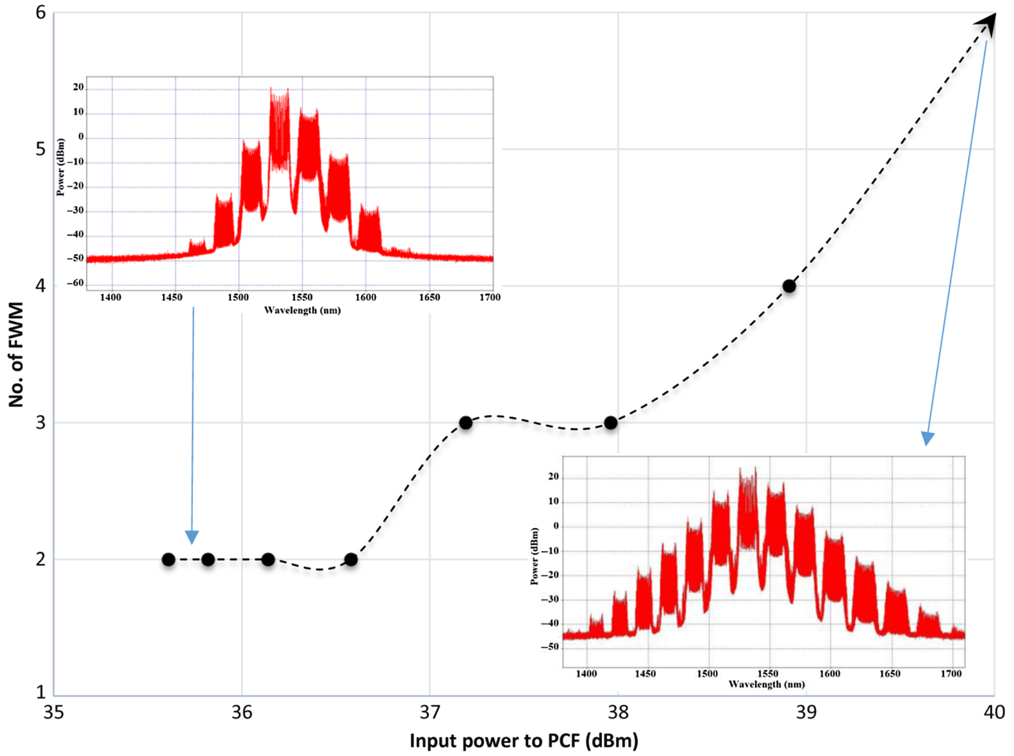

Fig. 6 Number of FWM orders versus input power to PCF.

$\Delta k_{NL} = C(P_1 + P_2)$, where P_1 and P_2 are the incident power of laser source 1 and 2, respectively.[5] Therefore, by adjusting Δk_{NL}, the phase matching condition can be achieved; hence, FWM occurred. Moreover, the generated FWM can interact with each other; then, more FWM can be generated. Furthermore, spacing between the two wavelengths should be chosen carefully to have more orders, as shown in Fig. 5. It was found that more FWM orders can be created as the spacing decreases; unfortunately an overlap between the orders occurs as the spacing becomes less than 15 nm. In addition, the number of FWM orders decreases as the spacing exceeds 23 nm. In conclusion, by tuning the second laser source within this range (Fig. 5), then broadened FWM combs can be achieved. It was found that, the number of FWM orders is same even with the RF signal at 10 GHz, except that the number of lines per FWM comb increases as RF increases. This means that FWM efficiency in terms of the number of orders does not depend on the RF signal as it does on input power to PCF as shown in Fig. 6. As long as the initial comb is generated and has enough power, then a cascaded FWM can be achieved.

4 Conclusion

In conclusion, this paper presents a simple configuration consisting of one laser source that is intensity modulated; then, the output is combined with another laser source, which is 23 nm apart from the first laser source wavelength. Then, the output phase is modulated. All is driven by a sinusoidal source with a frequency of 30 GHz. Hence, an initial comb was generated, used as a seed comb, and passed through 9-m PCF. Then, by controlling the spacing between the laser sources and the nonlinear coefficient of PCF, FWM exists and creates five to six orders. The generated wavelengths can be tuned in a range from ∼1400 to ∼1700 nm.

Acknowledgments

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