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Gain smoothening filter in two-segment fiber-optical parametric amplifier

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ABSTRACT

This paper demonstrates a method to remove the gain ripple profile specifically for a two-segment fiber optical parametric amplifier arising from the dispersion differences between the fiber gain medium and the standard single mode fiber attached to the optical components. This is achieved by using a simple design that incorporates a gain smoothening filter at the mid-stage of the amplifier. This simple yet practical method is useful when isolators are adopted for stimulated Brillouin scattering suppression but it comes with the expense of parametric gain.

1. Introduction

Fiber-optical parametric amplifier (FOPA) has been the subject of intensive research in recent years due to its useful features such as very high gain, wide gain bandwidth and inherent wavelength-conversion capability [1]. In most cases, the gain medium used in FOPA is a highly nonlinear fiber (HNLF) [2]. Since HNLF has a smaller core size, it is often necessary to suppress stimulated Brillouin scattering (SBS) generated by the strong pump wave in FOPA [3]. Pump dithering is the most common SBS suppression technique and is widely adopted in FOPA experiments, where the pump linewidth is actively broadened by phase modulating the pump light with RF tones/noise [4–6]. However, undesirable effects such as parametric gain modulation [7] might prevent FOPA with this technique to operate in ultra-high-gain regime. SBS threshold can also be increased by disrupting the SBS process in fiber, e.g. to apply stress [8,9] and temperature [10] along the fiber. One should take note that this particular method will also alter the fiber physical parameters such as the shift of fiber zero-dispersion wavelength and birefringence. In [9], distributed stress is applied on HNLF to minimize the zero-dispersion wavelength fluctuation in HNLF, but whether the suppression of SBS in the fiber is at its optimum condition still remains a question, in addition to the effect of tension-induced change of birefringence to the FOPA performance. Besides, other interesting SBS suppression techniques are also developed, including pump broadening by the cross-phase modulation method [11] and doping with aluminum oxide in the fiber core [12]. However the former allows only limited manipulation on the pump light spectrum for maximum SBS suppression, while the later comes with attenuation as high as 30 dB/km in the fiber which is detrimental to FOPA performance.

Another practical method is to use isolator, which suppresses SBS passively and can avoid all the undesirable effect mentioned earlier. In [13], SBS suppression of 3 dB has been demonstrated by separating two-segments of HNLF with an isolator, and transmission of 10 Gbps is successfully performed. However, due to the dispersion profile mismatch between HNLFs and the single mode fiber (SMF) of the isolator, the gain shows multiple peaks across the wavelength range and this problem is left unsolved.

In this letter, we demonstrate a method to rectify the gain modulation problem by removing the idler generated in the first HNLF section. This is achieved by using a simple filtering design that consists of a C/L-band wavelength-division multiplexer (C/L-WDM) and an ITU dense wavelength-division multiplexer (DWDM) filter, but with tolerable gain losses.

2. Theory

In a one-pump FOPA configuration, an intense pump with wavelength ω_p is injected into a HNLF along with a relatively low-power signal at ω_s. An idler at $\omega_i = 2\omega_p - \omega_s$ is automatically generated to fulfill the conservation of energy and momentum

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relation of photons. The underlying equations that govern the operation of FOPA are known as follows [14]:

$$\frac{dP_p}{dz} = -\alpha P_p - 4\gamma (P_p{}^2 P_s P_i)^{1/2} \sin\theta, \quad (1)$$

$$\frac{dP_s}{dz} = -\alpha P_s + 2\gamma (P_p{}^2 P_s P_i)^{1/2} \sin\theta, \quad (2)$$

$$\frac{dP_i}{dz} = -\alpha P_i + 2\gamma (P_p{}^2 P_s P_i)^{1/2} \sin\theta, \quad (3)$$

$$\frac{d\theta}{dz} = \Delta\beta + \gamma\Big\{2P_p - P_s - P_i + \big[(P_P{}^2 P_s/P_i)^{1/2} + (P_P{}^2 P_i/P_s)^{1/2} - 4(P_s P_i)^{1/2}\big]\cos\theta, \quad (4)$$

where P_p is the pump power, P_s is the signal power and P_i is the idler power. The fiber loss coefficient is represented by α while γ denotes the fiber nonlinear coefficient. $\Delta\beta = \beta_s + \beta_i - 2\beta_p$ is the phase-mismatch parameter withβ_s, β_i and β_p representing the propagation constants for signal, idler and pump light respectively. Normally, $\Delta\beta$ is approximated to Taylor series expansion and its equation can be rewritten as [15]

$$\Delta\beta = \beta_2(\omega_s - \omega_p)^2 + \beta_4(\omega_s - \omega_p)^4/12 \quad (5)$$

In addition, θ is the phase relation of all three waves traveling in the medium and is defined as

$$\theta(z) = \Delta\beta z + \phi_s(z) + \phi_i(z) - 2\phi_p(z), \quad (6)$$

where ϕ_s, ϕ_i and ϕ_p are the phases for the signal, idler and pump respectively. Referring to Eqs. (1)–(3), it is obvious that the phase relation θ determines the sign of the coupled equations. If $\sin\theta > 0$, parametric amplification takes place and power from pump will transfer to signal and idler. Similarly, if $\sin\theta < 0$, power is transferred from signal/idler back to the pump. As shown in Eqs. (4) and (6), θ is altered by the phase-mismatch parameter $\Delta\beta$, which depends largely on the second order dispersion value of fiber. As a result, the modulation of θ leads to the wavelength-dependent gain fluctuation [16,17].

3. Experiment and result

Fig. 1 shows the experimental setup of single-pump two-segment FOPA design with an idler removal filter (IRF). One tunable laser source (TLS1) is used as a parametric pump. At the pump arm, a polarization controller (PC) is used to align the pump light polarization before entering a phase modulator. A phase modulator is used to modulate the pump light with 4 sinusoidal RF tones: 96 MHz, 312 MHz, 906 MHz and 2.64 GHz in order to increase the SBS threshold. The pump light is then boosted up by a high power erbium-doped fiber amplifier (EDFA) with maximum output power of 1 W, and a tunable bandpass filter (TBF) is placed after it to filter out the amplified spontaneous emission. The signal arm comprises of another tunable laser source (TLS2), a PC to control the signal polarization and a circulator to monitor the SBS reflected power. A 90/10 coupler is used to multiplex pump from TLS1 and signal from TLS2 into the two-segment HNLF with equal length of 500 m in each segment. The first section of HNLF has a zero dispersion wavelength at 1556.5 nm, while the second section of HNLF has a zero dispersion wavelength at 1557.6 nm. However both sections have found to have the same nonlinear coefficient 11.5/W/km and dispersion slope 0.015 ps/nm^2/km. In between the HNLF spools, an isolator and an IRF are inserted. The purpose of isolator is to increase the SBS threshold by 3 dB [13], while the IRF is used to smoothen the parametric gain bandwidth. Two IRF designs are shown in inset 1 and inset 2 to cater for C-band and L-band signal amplification respectively. The C/L-WDM has a 3 dB cut-off at 1565 nm for the C-band transmission, while the ITU filter has a 100 MHz passband at 1560.6 nm. Lastly, a 98/2 coupler is placed at the output to tap the gain spectrum of the amplifier.

As mentioned earlier, the conventional isolator is made using SMF and has different dispersion properties from HNLFs. The dispersion mismatch of these two fiber types disrupts the phase relation of the pump, signal and generated idler as suggested by Eq. (6) which causes gain fluctuation across wavelengths. This can be clearly seen from the amplified quantum noise of the FOPA at 1 W, 1560.5 nm pump with isolator but without an IRF as depicted in Fig. 2. By inserting either IRF1 or IRF2 after the isolator, the noise envelope is smoothened, evidenced by the smooth lines. The essence of this filter will be presented later.

Further investigation on the uneven gain characteristic of this FOPA is carried out and the results are shown in Fig. 3. The solid black line is numerically simulated using Eqs. (1)–(6), while the red line with markers is the experimental result with 1 W of pump power at 1560.5 nm. In the simulation, the pump power is adjusted to match with the experimental data. The simulation is performed in three steps [16]. In the first step, an intense pump, a signal and a very small power idler are input into the first segment HNLF. Next, at the output of the first segment of HNLF, the parameter θ is replaced with $\theta' = \theta + \Delta\beta_{SMF} L_{SMF}$ to manifest the modulation of θ. In this step, we assume that the nonlinearity of the SMF is negligible and hence no significant power transfer occurs between pump and signal/idler due to the parametric process. In the third step, we utilize pump, signal and idler from the first segment of HNLF together with the new θ' into the subsequent segment of HNLF and the final data at the output is obtained.

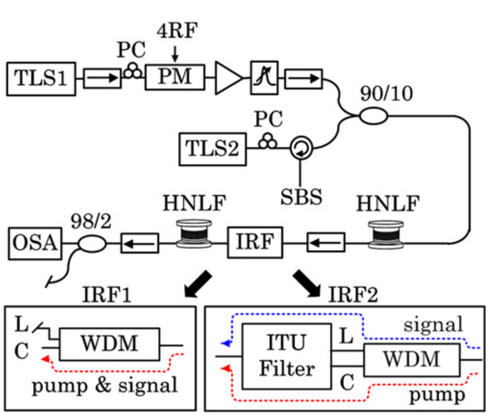

Fig. 1. Experimental setup of two-segment FOPA with option of IRF1 and IRF2 for C-band and L-band signal respectively.

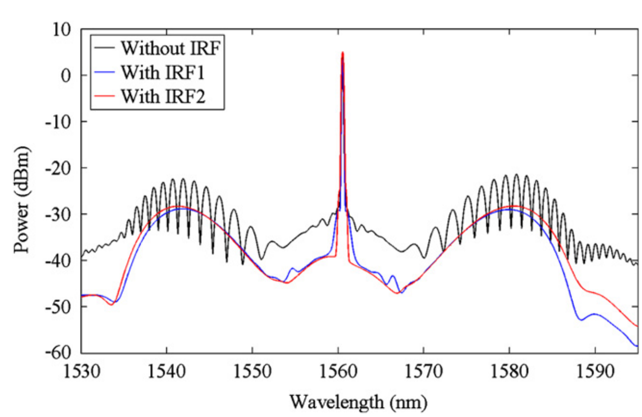

Fig. 2. Amplified quantum noise of two-segment FOPA measured with optical spectrum analyzer.

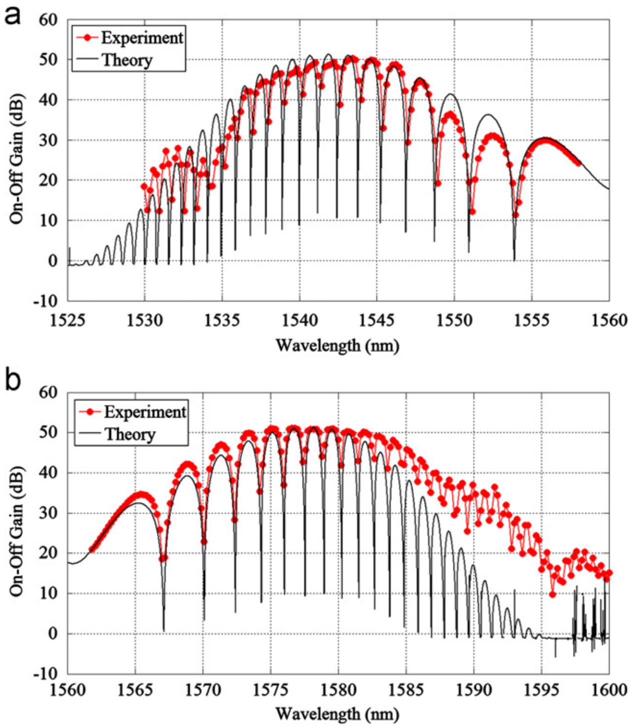

Fig. 3. (a) C-band on–off gain and (b) L-band on–off gain of two-segment FOPA with isolator but without IRF.

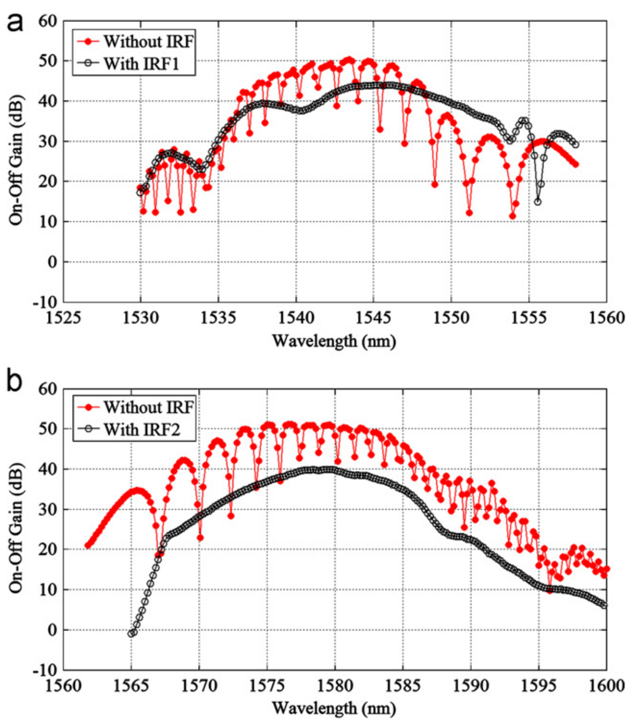

Fig. 4. (a) C-band on–off gain and (b) L-band on–off gain of two-segment FOPA with isolator and/without IRF.

In order to smoothen the gain fluctuation profile of this FOPA structure, an IRF is used. Its function is to suppress the idler component at the mid-stage, so that a new idler with a correct phase in relation with those of pump and signal can be regenerated in the second segment of the HNLF, hence restoring the desired gain profile. Fig. 4(a) compares the on–off gain of two-segment FOPA with and without IRF1 at 1 W pump power and 1560.5 nm pump wavelength. The IRF1 is actually a C/L-WDM with port L is properly terminated and it has a 3-dB cutoff point around 1565 nm. This means that it removes the mid-stage L-band idler component and allows only the C-band components, i.e. pump and signal, to enter the second section of HNLF.

On the other hand, the gain profile is not entirely smooth that most likely due to some residual SMF phase-mismatch exists at the FOPA mid-stage. To investigate the gain characteristic in the L-band, an IRF2 is used at the mid-stage. The ITU filter has 100-GHz wide passband at 1560.6 nm, which permits the propagation of the pump and couples the L-band signal into the second section of HNLF while blocking the C-band idler. As a result, the gain in L-band is flattened as shown in Fig. 4(b). However the smoothened gain is slightly lower than their original values. Beside passive power loss in the smoothening filter, this gain reduction can be explained by looking at the gain equation for a length L FOPA: $G=\exp(2\gamma P_p L)/4$[1]. The gain smoothening filter in the mid-stage effectively segmented the FOPA fiber length into $L/2$, and result in an effective gain of $G_{eff}=\exp(2\gamma P_p L/2)/4\ \exp(2\gamma P_p L/2)/4=G/4$, which is about 6 dB reduction. Since FOPA is a high gain device, as we can see in this experiment the peak gain is near 50 dB, the gain losses caused by IRF or smoothening filter is still tolerable.

4. Conclusion

In conclusion, we have demonstrated a method to smoothen the gain modulation profile in a two-segment FOPA which is induced by the dispersion mismatched condition. By filtering the idler at the FOPA mid-stage, the gain fluctuations are minimized in addition to SBS suppression, but come with the cost of slight gain reduction. This idea can also be extended and modified to become a multiple-segment FOPA with several useful functions e.g. multipoint broadcasting or multiple idler/signal wavelength duplication, without compromising on the gain profile, as long as the gain loss is below certain tolerable threshold.

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