Numerical analysis for four-wave mixing based wavelength conversion of differential phase-shift keying signals

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We numerically investigate the main constrains for high efficiency wavelength conversion of differential phase-shift keying (DPSK) signals based on four-wave mixing (FWM) in highly nonlinear fiber (HNLF). Using multi-tone pump phase modulation techniques, high efficiency wavelength conversion of DPSK signals is achieved with the stimulated Brillouin scattering (SBS) effects effectively suppressed. Our analysis shows that there is a compromise between conversion efficiency and converted idler degradation. By optimizing the pump phase modulation configuration, the converted DPSK idler's degradation can be dramatically decreased through balancing SBS suppression and pump phase modulation degradation. Our simulation results also show that these multi-tone pump phase modulation techniques are more appropriate for the future high bit rate systems.

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Wavelength converters are important building blocks in wavelength division multiplexing (WDM) networks[1]. Fiber-based wavelength conversion techniques relying on four-wave mixing (FWM) have received a lot of attention recently due to its virtue of tunability, cascadibility, and transparency to bit rate and modulation formats[2−4]. In practical applications, stimulated Brillouin scattering (SBS) is the main constrain for the FWM-based wavelength conversion techniques, and pump phase modulation techniques can be used to effectively suppressed the SBS effects[5,6]. Differential phase-shift keying (DPSK) format has attracted much attention recently because of its 3-dB benefit in receiving sensitivity and superior tolerance to fiber nonlinearities[7]. Many methods have been used to perform wavelength conversion of DPSK signals[8], and a maximum conversion efficiency of 85% has been achieved by using FWM in highly nonlinear fiber (HNLF)[9].

In this letter, we quantitatively investigate the pump phase modulation techniques for suppressing the SBS effects together with its influence on conversion efficiency and the converted signal (idler) quality for DPSK signals. By separately discussing the SBS suppression and pump phase modulation degradation, their respective attribution to the idler quality can be clearly seen. We also point out that the converted DPSK idler's degradation can be dramatically decreased through balancing SBS suppression and phase modulation degradation.

The system setup in our simulation is shown in Fig. 1. One channel carrying 40-Gb/s non-return-to-zero (NRZ)-DPSK signal is launched into a spool of 1200-m-long HNLF together with a strong continuous-wave (CW) pump. The HNLF has a zero-dispersion wavelength of 1545 nm, a nonlinear coefficient of 12 $\mathrm{W^{-1}\cdot km^{-1}}$ with a dispersion slope of 0.016 ps/($\mathrm{nm^2\cdot km}$). And its SBS bandwidth is 35 MHz with a Stokes frequency shift of 11 GHz.

Our numerical simulations are performed with VPI-transmissionMaker7.5. We choose the length of a De Bruijn sequence as 4096 bits to contain sufficient bit patterns to capture nonlinear interaction details for the system scenarios[10]. We use a Chi2_ISI estimation method for bit error rate (BER) estimation by using the fourth-order Bessel electrical low-pass filter with 30-GHz bandwidth. For DPSK signals, BER were estimated with direct detection balanced receivers by taking into account the inter-symbol interference (ISI)[11]. It should be noted that we do not taking stimulated Raman scattering into consideration, for the pump power used in the simulations are well below the Raman threshold power[12]. In order to take the explicit interaction between different channels into consideration, we use single frequency band sampling by simultaneously sampling the pump, signal, conjugate, and even higher order FWM products. In our cases, the sampling bandwidth is 5120 GHz centered at 194.0 THz by using single frequency band sampling.

The efficiency of wavelength conversion in an ideal FWM process can be expressed as[8]

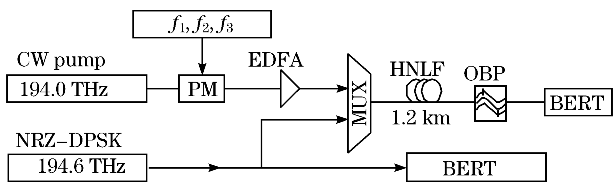

Fig. 1. System configuration for DPSK wavelength conversion with pump phase modulation. PM: phase modulator; EDFA: erbium-doped fiber amplifier; MUX: multiplexer; OBP: optical bandpass filter; BERT: bit error rate tester.

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$$\eta_{\text{ideal}} = \sinh^2(\gamma P_{\text{P}} L), \quad (1)$$

where γ is the nonlinear coefficient of the fiber, P_{P} is the pump power transmitted through the fiber, and L is the length of the fiber. Neglecting the loss in the fiber, the pump power for 100% wavelength conversion efficiency can be calculated using Eq. (1) to be $\sim$ 60 mW. In our simulation, the signal power launched into the HNLF is 1 mW, while the CW pump power is 80 mW by taking into account the fiber loss and energy transfer from CW pump to signal, conjugate, and higher order FWM products.

To be useful in a wide range of communication applications, the conversion efficiency should be higher than 0 dB, in order to avoid the substantial signal-to-noise ratio (SNR) degradation and achieve concatenated wavelength conversion[5]. So pump phase modulation is needed when the SBS effects are strong enough and the transmitted CW pump power is limited to a relatively low level. In order to effectively suppress the SBS effects, one to three tones (50, 150, and 450 MHz) were used to phase-modulate the pump. The frequencies were chosen to provide a flat pump power spectrum separated by 50 MHz[6], which is higher than the Brillouin gain bandwidth of 35 MHz. From Fig. 2 we can see that by using phase modulation, the pump power that can be transmitted through the HNLF is increased dramatically.

DPSK idlers will be distorted by the high frequency phase modulation applied to the pump, because pump phase modulation will imprint on the idlers via the phase coupling nature of the FWM process and seriously degrade the idlers. The SBS effects will also affect the idlers

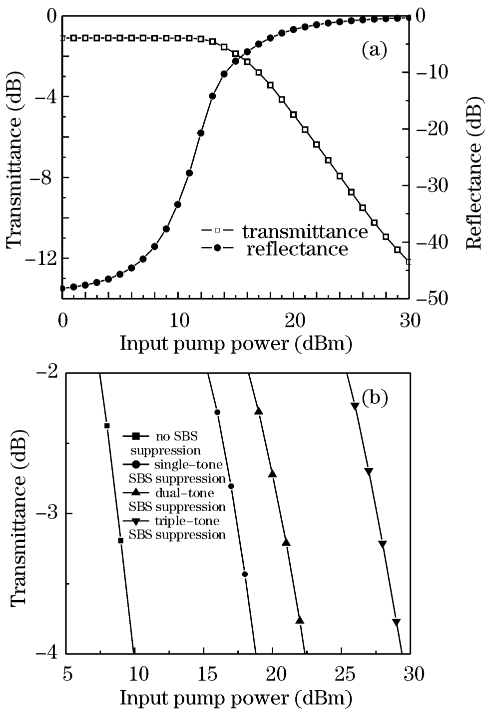


Fig. 2. (a) Transmittance and reflectance from 1200-m HNLF as a function of input pump power with single-tone pump phase modulation for SBS suppression. (b) Transmittance as a function of input power without SBS suppression and with SBS suppression using one to three tones pump phase modulation.

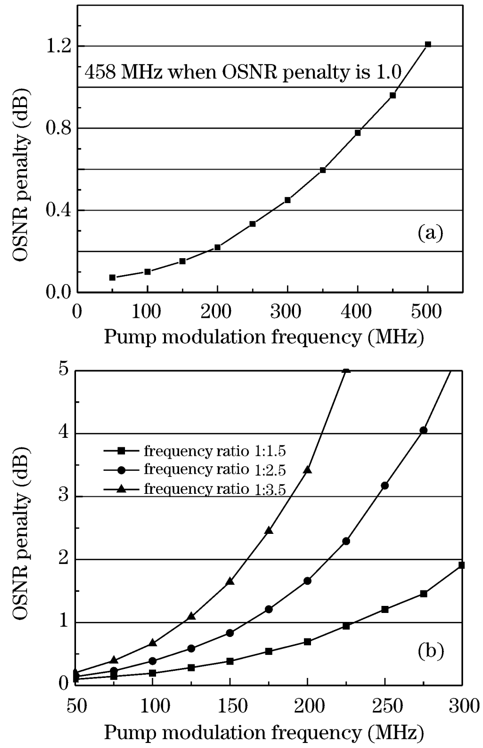


Fig. 3. OSNR penalty at the BER of 10^{-3} versus pump modulation frequency for (a) single- and (b) dual-tone phase modulation. The x axis stands for the lower phase modulation frequency.

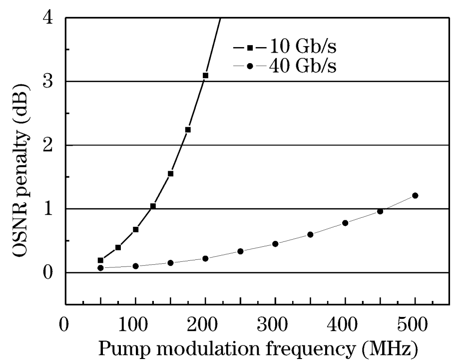


Fig. 4. OSNR penalty at the BER of 10^{-3} versus phase modulation frequency for different signal bit rates.

as it will cause pump power fluctuation which will be transferred to gain distortions if the input pump power is higher than a certain level (SBS threshold power). High frequency phase modulation will degrade the converted DPSK idlers, but it is beneficial for improving the maximum CW pump power into the HNLF by using multi-tone phase modulation. From the view point of practical application, there is a compromise between SBS suppression and phase modulation degradation.

For the case when the signal bit rate B is much higher than the maximal modulational frequency $f_{\max}$, $B \gg f_{\max}$, the maximal differential phase distortion induced by the pump phase modulation can be calculated by[2]

$$\Delta\phi_{\text{mod}}^{\max} \cong 4\pi\left(m_1\frac{f_1}{B} + m_2\frac{f_2}{B} + m_3\frac{f_3}{B} + \cdots\right), \quad (2)$$

where m_i are modulation indices and f_i are modulation frequencies. For simplicity, m_i are chosen to be equal (π rad) to obtain an advantageous spectral distribution.

The numerical results shown in Fig. 3 for which we do not consider the SBS effects and just find the impact of pump phase modulation on the converted idler. They are in accordance with the analytical result of Eq. (2). Under the situation of single-tone phase modulation, the idler's optical signal-to-noise ratio (OSNR) penalty at the BER of 10^{-3} will increase with the pump phase modulation frequency. In order to keep the OSNR penalty below 1.0 dB, the pump modulation frequency should be smaller than 458 MHz. For the following discussions, we can use this standard (1-dB OSNR penalty) to evaluate the influence on idler for different pump phase modulation configurations. Under the situation of dual-tone pump phase modulation, the idler undergoes greater degradation with the increase of pump phase modulation frequency f_1 and frequency ratio. For triple-tone and even more tones pump phase modulation, results are similar to the above single- and dual-tone cases. In order to minimize the phase distortion induced by pump phase modulation, the pump phase modulation frequency must be chosen as small as possible.

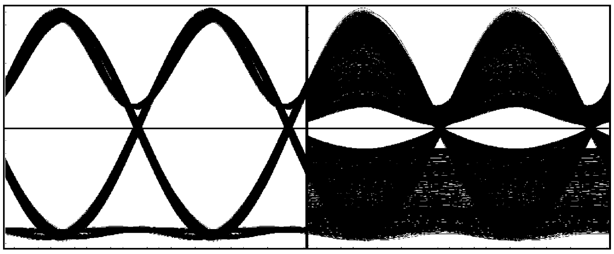
We also carry out further simulation with different signal bit rates for single-tone phase modulation, as shown in Fig. 4. It can be clearly seen that with the increase of signal bit rate, the maximum pump modulation frequency at 1-dB OSNR penalty will also increase. This can be easily understood because the frequency spectrum bandwidth of the signal is directly related to its bit rate. With the increase of signal bit rate, its frequency spectrum bandwidth will also expand, leading to better endurance of phase modulation distortion. It can be concluded that pump phase modulation techniques are more appropriate for high bit rate system. And our simulation results are in accordance with Eq. (2).

Now we put SBS effects into consideration. It has been pointed out that SBS effects will mainly act as amplitude fluctuation for CW pump if the launched CW pump power is higher than SBS threshold power. In the degenerate FWM, the idler is directly related to the CW pump and the original signal by

$$E_{\rm i} \propto E_{\rm p}^2 E_{\rm s}^*, \quad (3)$$

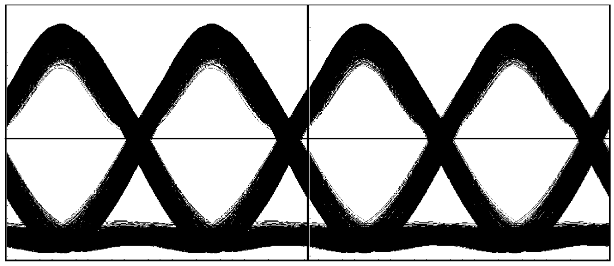
where $E_{\rm p}$, $E_{\rm s}$, and $E_{\rm i}$ are the complex amplitudes of the input pump, signal, and output idler. So it can be seen that the pump amplitude fluctuation caused by SBS will greatly influence the idler because the idler amplitude is proportional to the square of input pump's complex amplitude. SBS suppression techniques such as multi-tone pump phase modulation should be used to effectively suppress the pump amplitude fluctuation. From the above analysis, we know that high frequency pump phase modulation applied to the CW pump will cause serious idler phase degradation which limits the maximum pump phase modulation frequency at low idler degradation. So a compromise should be made to balance the SBS suppression and phase modulation degradation.

Now we compare the results for dual-tone pump phase modulation (Fig. 5) and triple-tone pump phase modulation (Fig. 6). From the results we can see that under the case of dual-tone phase modulation configuration,



(a) (b)

Fig. 5. Eye diagrams for dual-tone phase modulation (a) without taking SBS effects into consideration (0.17-dB OSNR penalty) and (b) with SBS effects (3.10-dB OSNR penalty).



(a) (b)

Fig. 6. Eye diagrams for triple-tone phase modulation (a) without taking SBS effects into consideration (1.21-dB OSNR penalty) and (b) with SBS effects (1.21-dB OSNR penalty).

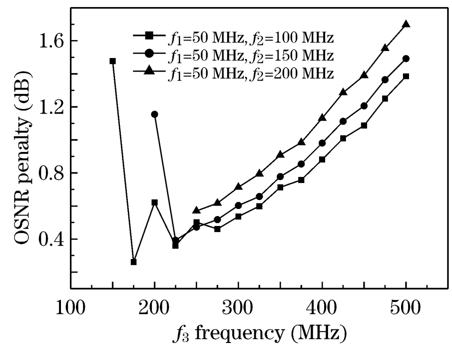


Fig. 7. OSNR penalty at the BER of 10^{-3} versus f_3 frequency for different pump phase modulation configurations.

SBS effects are not effectively suppressed, so the main contribution for idler degradation is due to SBS effects. And for the case of triple-tone phase modulation configuration, SBS effects are effectively suppressed, and the main constrain for idler quality is phase modulation distortion. We can see that pump phase modulation configuration can be optimized to achieve smaller idler degradation by properly balancing SBS suppression and phase modulation distortion.

The simulation results for triple-tone phase modulation configuration are shown in Fig. 7. It can be seen that by optimizing the pump phase modulation configuration, the idler degradation can be effectively decreased. With the configuration of f_1=50 MHz and f_2=150 MHz, the idler degradation can be decreased to 0.39 dB by appropriately choosing f_3 frequency. And the results also show that the idler degradation can be further decreased by optimizing the pump phase modulation configuration. It can be concluded from the results that under a low pump phase modulation frequency f_3, SBS-induced pump power fluctuation is the main cause for idler degradation due to ineffective SBS suppression. The fluctuation of idler degradation at low f_3 frequency is also attributed to the different pump power distributions caused by the change of the dominating harmonic. While under a high pump phase modulation frequency, the SBS effects are effectively suppressed and the main cause for idler degradation is pump phase modulation degradation. By further optimizing the pump phase modulation configuration, the idler degradation as low as 0.26 dB can be obtained.

We have shown that the maximum pump modulation frequency for single-tone pump phase modulation will increase with the increase of signal bit rate. So the multi-tone pump phase modulation configuration can be more easily chosen to achieve smaller idler degradation for the future systems with 100-Gb/s and even higher bit rates. As for the 10-Gb/s system, because of the limitation of maximum pump modulation frequency, high efficiency wavelength conversion of DPSK signals with small idler degradation cannot be achieved. Some other methods such as temperature and strain distribution[13,14] should be used to further decrease the SBS effects in order to achieve high efficiency wavelength conversion while maintaining small idler degradation. But these additional methods will complicate the system design and application. So the multi-tone pump phase modulation techniques are more appropriate especially for the future high bit rate systems.

The above discussion is focused on degenerate FWM wavelength conversion techniques which are polarization sensitive. The change of polarization state will also affect the conversion efficiency, leading to the idler amplitude fluctuation[4]. In order to achieve the maximum conversion efficiency, the polarization states of signal and pump should be identical. But our discussion can be further extended to non-degenerate cases. Polarization insensitive operation can be achieved using non-degenerate FWM with two orthogonal pumps[15].

It should be pointed out that different HNLFs have different SBS thresholds and many other methods have been proposed to suppress the SBS effects. So the SBS threshold and pump phase modulation configuration may be quite different for various HNLFs. And with the emerging of microstructure fiber and ultra-high-nonlinear fibers such as bismuth oxide fiber, the SBS effects are greatly reduced and in some cases can be neglected. DPSK signals show their advantage over on-off keying (OOK) signals in wavelength conversion applications, especially in multi-channel cases, because OOK signals will suffer from serious data-pattern-dependent pump depletion degradation.

In conclusion, we numerically explore the high efficiency wavelength conversion techniques for DPSK signals which have not been studied extensively compared with OOK signals. We also investigate pump phase modulation techniques for suppressing the SBS effects together with their influence on conversion efficiency and idler quality. Our analysis shows that there is a compromise between SBS suppression and pump phase modulation degradation. By optimizing the pump phase modulation configuration, the converted DPSK idler degradation can be effectively decreased. The experimental researches on high efficiency wavelength conversion of DPSK signals with small idler degradation are in progress.

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