Numerical analysis of four-wave-mixing based multichannel wavelength conversion techniques in fibers*

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Abstract: We numerically investigate four-wave-mixing (FWM) based multichannel wavelength conversion for amplitude-modulated signals, phase-modulated signals, together with mixed amplitude and phase modulated signals. This paper also discusses the influence of stimulated Brillouin scattering (SBS) effects on high-efficiency FWM-based wavelength conversion applications. Our simulation results show that DPSK signals are more suitable for FWM-based multichannel wavelength conversion because the OOK signals will suffer from the inevitable data-pattern-dependent pump depletion. In future applications, when the modulation format is partially upgraded from OOK to DPSK, the influence of OOK signals on the updated DPSK signals must be considered when using multichannel wavelength conversion. This influence becomes severe with the increase of OOK channel number. It can be concluded that DPSK signals are more appropriate for both transmission and multichannel wavelength conversion, especially in long haul and high bit-rate system.

Key words: stimulated Brillouin scattering; wavelength conversion; four-wave mixing; nonlinear optics
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1. Introduction

All-optical wavelength converters are important building blocks for a flexible network topology in wavelength division multiplexing (WDM) networks and have been explored extensively during the past decade[1]. Many methods have been proposed to realize all-optical wavelength conversion based on different materials and nonlinear effects. Among them, fiber-based wavelength conversion techniques relying on four-wave-mixing (FWM) are very advantageous in terms of tunability, cascadibility, and transparency to bit rate and modulation formats[2,3].

In practical applications, stimulated Brillouin scattering (SBS) is the main constrain for this FWM-based wavelength conversion technique because SBS has the lowest threshold for the high power CW pump. Differential phase-shift keying (DPSK) format has received a lot of attention recently due to its virtues of 3 dB benefit in receiving sensitivity and superior tolerance to fiber nonlinearities[4]. DPSK is more suitable for high-speed and long-haul WDM transmission, especially when the date rate is 40 Gbit/s and beyond. So in the future, the traditional modulation format OOK and the updated modulation format DPSK may co-exist in backbone long-haul transmission lines. To facilitate the maintenance of all-optical networks, we need to consider the situation when amplitude-modulated and phase-modulated signals co-exist in the transmission links and are simultaneously wavelength converted for applications such as network blocking alleviation and network broadcast.

In this paper, we investigate the SBS suppression techniques and discuss the influence of pump phase modulation on the quality of the converted signals (idlers). And we also present the detailed numerical analysis for multichannel wavelength conversion techniques when the SBS effect can be neglected.

2. SBS suppression technique

To be useful in a wide range of communication applications, the FWM conversion efficiency should be higher than 1, in order to avoid a substantial signal-to-noise ratio degradation and to achieve concatenated wavelength conversion. However, the maximum conversion efficiency for a CW pump based FWM process is limited by the maximum pump power that can be transmitted down the fiber. The SBS effect seriously limits the total amount of pump power that can be transmitted through the fiber. The SBS effect will also affect the idler as it will cause pump power fluctuations, which will transfer to idler gain distortions if not effectively suppressed.

Two techniques can be used to effectively suppress the

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SBS effect and enhance the maximum CW pump power in the fiber: (1) Broadening the Brillouin gain bandwidth by varying the frequency of the acoustic wave along the fiber[5–7]; (2) Broadening the laser linewidth by phase modulation[8, 9].

The frequency of the acoustic wave along the fiber can be adjusted by varying the core radius[5] and dopant concentration[6], the temperature and strain distribution[7], etc. When the frequency of the acoustic wave is varied along z direction, the maximum effective gain factor will decrease and the SBS threshold will increase.

Because SBS has a very narrow bandwidth, phase modulation techniques may be used to spectrally broaden the CW pump spectrum beyond the SBS gain bandwidth. The spectral distribution into sidebands will effectively suppress the SBS effect and consequently enhance the Brillouin threshold. In order to effectively suppress the SBS effect, binary phase-shift keying (BPSK) signals or a multifrequency scheme using several sinusoidals can be used to spectrally broaden the pump[8, 9]. The multifrequency scheme is more preferable, especially in multichannel applications.

For the case when the signal bit rate B is much higher than the maximal modulation frequency $f_{\max}$, $B \gg f_{\max}$, the maximal differential phase distortion induced by the pump-phase modulation can be calculated by[9]

$$\Delta\phi_{\text{mod}}^{\max} \cong 4\pi\left(m_1\frac{f_1}{B} + m_2\frac{f_2}{B} + m_3\frac{f_3}{B} + \cdots\right), \tag{1}$$

where m_i and f_i are modulation indices and frequencies. It can be clearly seen that with the increase of the signal bit rate, phase distortion induced by the pump-phase modulation will decrease, implying that this technique is more suitable for high bit-rate applications.

It should be pointed out that different HNLFs have different SBS thresholds, and many other methods have been proposed to suppress the SBS effect[10]. And with the emergence of microstructure fibers and ultra-high-nonlinear fibers, such as Bismuth oxide fibers, the SBS effect is greatly reduced and in many cases it may be neglected. And in the above analysis, we have shown that if pump phase modulation is applied to suppress the SBS effect, it will mainly act as a differential phase distortion for the DPSK signals. So, in the following analysis, we may neglect the SBS effect and simply consider the other effects for multichannel wavelength conversion applications.

3. Analysis of multichannel wavelength conversion techniques

Wavelength converters operating only in single channel mode are cumbersome for flexible network management. So, the ability to convert many channels in a single wavelength converter is highly desirable, for it can lead to a simple network topology infrastructure. Multichannel wavelength conversion of DPSK signals has been achieved by using FWM in highly nonlinear fibers (HNLF)[3]. A maximum conversion efficiency of 85% has been achieved for both NRZ and return-to-zero DPSK signals. But up to now, wavelength conversion for mixed amplitude-modulated and phase-modulated formats has not been considered and demonstrated. So, for the first time, we numerically investigate the situation when different modulation formats are used for wavelength conversion applications.

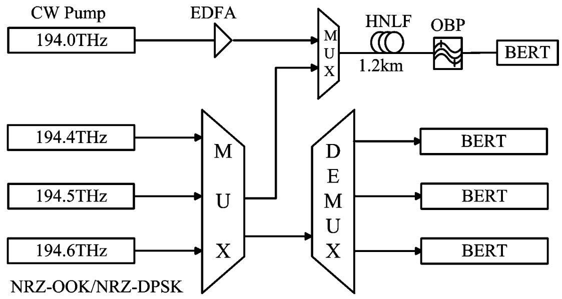

Fig. 1. System configuration in our simulation.

The system setup in our simulation is shown in Fig. 1. Three channels carrying 40-Gbit/s NRZ-OOK or NRZ-DPSK signals are launched into a spool of HNLF together with a strong CW pump. The fiber used in our simulation is a 1200-m-long piece of HNLF. The HNLF has a zero-dispersion wavelength (λ_0) of 1545 nm, a nonlinear coefficient of 12 $W^{-1}\cdot km^{-1}$ with a dispersion slope of 0.016 ps/(nm$^2\cdot$km). The frequency of the CW pump is 194.0 THz and is chosen to be close to the zero-dispersion wavelength of HNLF.

Our numerical simulations are performed with VPItransmissionMaker7.5. We choose the length of a De Bruijn sequence as 4096 bits to contain sufficient bit patterns to capture the nonlinear interaction details[11]. The performance of our system is evaluated by measuring the bit-error-rate (BER). We use a Chi2_ISI estimation method for the BER estimation by using a fourth-order Bessel electrical low-pass filter with a 30 GHz bandwidth. For the DPSK signals, the BER was estimated with direct detection balanced receivers by taking the intersymbol interference (ISI) into account. It should be noted that we do not take stimulated Raman scattering into consideration, as the pump power used in the simulations is 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 pump, signal, conjugate and even higher order FWM products. In our cases, the sampling bandwidth is 5120 GHz and centered at 194.0 THz.

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

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

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. Using Eq. (2) and neglecting the loss in the fiber, the pump power for 100% wavelength conversion efficiency can

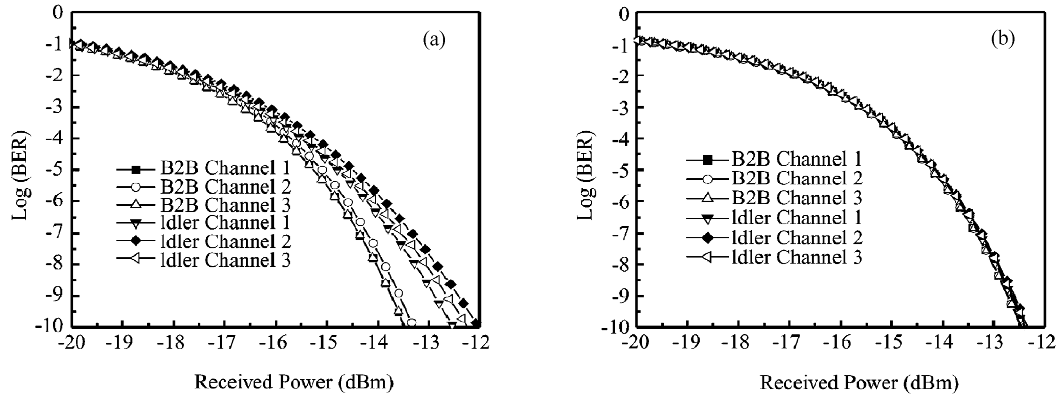

Fig. 2. BER for (a) a three-channel OOK and (b) a three-channel DPSK wavelength conversion idlers.

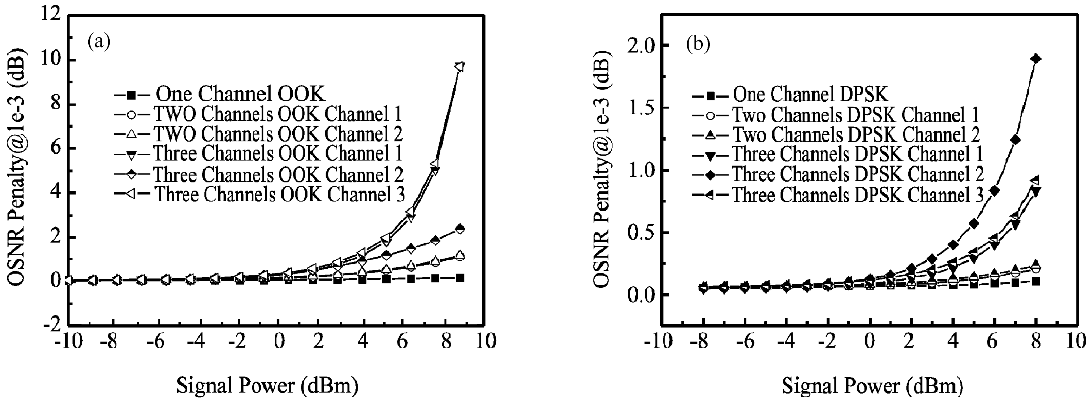

Fig. 3. OSNR penalty versus signal power for multichannel: (a) OOK; (b) DPSK idlers.

be calculated to be ~60 mW.

First, we consider the situation of multichannel OOK or DPSK wavelength conversion. The signals were filtered by a third-order Gaussian bandpass filter with a bandwidth of 80 GHz and multiplexed with a channel spacing of 100 GHz. The signal power launched into the HNLF is 1 mW, while the CW pump power is 80 mW, taking into account the fiber loss and the energy transfer from the CW pump to signal, conjugate and higher order FWM products. It has been pointed out that OOK data-pattern-dependent pump-depletion induced penalties become severe when the total signal power in all the channels reaches within ~10 dB of the pump power; these results place a constraint for wavelength conversion of multiple OOK signals[3, 13]. Compared with OOK signals, DPSK signals have the advantage of a constant optical power over the bits regardless of the data pattern. From Fig. 2, we can see that under such conditions, the difference between the converted DPSK idlers and the original DPSK signals is negligible. This shows that the signal launch power is relatively low and the interchannel crosstalk between different DPSK signals can be neglected. Compared to the three channels DPSK wavelength conversion, the three channels OOK wavelength conversion is affected by degradation (0.5 dB at a BER of 1.0×10^{-9}) due to data-pattern-dependent pump depletion.

It should be pointed out that we consider both cases, with and without pump EDFA noise. Simulation results show a negligible difference between both cases. This may be due to the high OSNR ratio of the signal and the usage of a narrow band optical filter (0.8 nm) to exclude the outband ASE noise of the CW pump. So, in the following analysis, we can use a simpler way of OSNR penalty to evaluate the idler's performance.

The OSNR penalty is defined as the difference of the required OSNR at a BER of 1×10^{-3} (representing the target BER for forward-error correction) between the converted idler and the original signal. In order to show the differences between the OOK and DPSK wavelength conversion techniques more clearly, the OSNR penalty is plotted verses different signal launch powers in Fig. 3.

It can be seen that with an increase of the signal power launched into the HNLF, the degradation for OOK and DPSK idlers will both increase. And with the increasing of signal channel numbers, the converted idlers will suffer a greater penalty, because the signals will interact with each other and affect the idlers. It should be pointed out that compared with DPSK idlers, OOK idlers will suffer a great degradation in multichannel applications because of the data-pattern-dependent pump depletion[3, 13]. At a signal power of 5 dBm, OOK idlers will undergo a penalty of about 2 dB for three-channel configuration. But for three-channel DPSK configuration, the idlers will undergo a penalty of about 2 dB at a signal power of 8 dBm. Three are about 3 dB benefits of signal launch power for DPSK signals comparing to OOK signals at multichannel cases. So, DPSK signals are more suitable for multichannel wavelength conversion applications. The signal

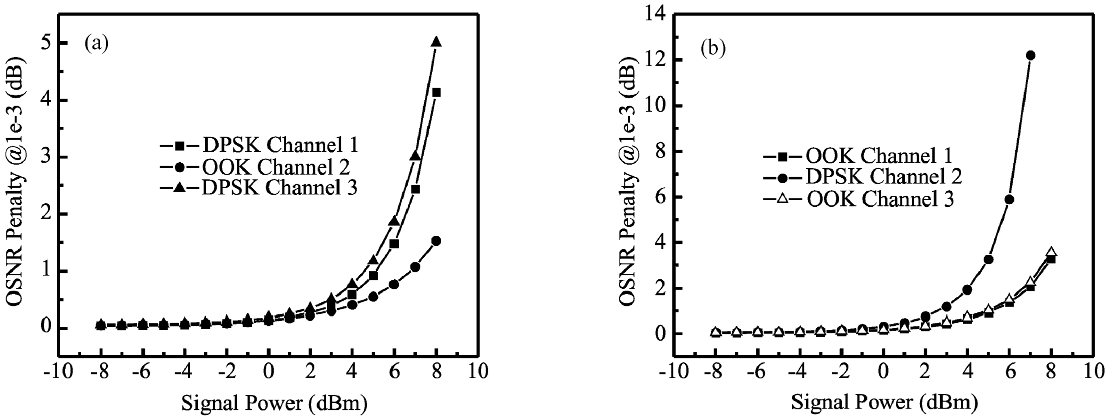

Fig. 4. OSNR penalty versus signal power for (a) 1ChOOK & 2ChDPSK and (b) 2ChOOK & 1ChDPSK.

power and channel number can be flexibly chosen to fit the different demands for network administration. For three-channel OOK configuration, where the data-pattern-dependent pump depletion is the main degradation sources for idlers, the middle channel idler will suffer less penalty comparing to its neighboring two channels. For DPSK idlers, the degradation at high signal launch power may be attributed to the strong cross-phase modulation between different channels. And in three-channel DPSK configuration, the middle channel will suffer a greater degradation because the neighboring two channels will both contribute to the middle idler channel degradation.

In future all-optical networks, amplitude-modulated and phase-modulated signals may co-exist in the transmission line. So, it is necessary to consider the situation when amplitude-modulated and phase-modulated signals are simultaneously wavelength converted.

From Fig. 4(a), we can see that the middle OOK signal greatly influences the neighboring two DPSK idlers. At a signal power of 6 dBm, it will induce around 1.0 dB OSNR penalty for its neighboring DPSK idlers. Compared to three-channel DPSK wavelength conversion techniques, the introduction of the middle OOK channel will induce a greater penalty on its neighboring DPSK idlers because of a data-pattern-dependent pump depletion of the OOK signal. From Fig. 4(b), we can see that the neighboring two OOK channels will greatly influence the middle DPSK idler. At a signal power of 6 dBm, the middle DPSK idler will suffer an OSNR penalty of 6 dB, while in the cases of three channel OOK wavelength conversion techniques the middle OOK channel will suffer an OSNR penalty of about 2 dB. We can see that for the same signal launch power of 6 dBm, the middle DPSK channel will undergo excess penalty of about 4 dB for the severe amplitude and phase distortions caused by the neighboring two OOK channels.

From the results, we can clearly see that with the increasing of OOK channel numbers, the idler quality will be severely degraded, especially for DPSK idlers. DPSK idlers will be greatly influenced by the neighboring OOK signals, and this degradation is more pronounced with the increase of OOK channel number.

In future applications, when the modulation format is partially upgraded from OOK to DPSK, the influence of OOK signals on the DPSK signals must be considered. DPSK signals have advantages over OOK signals when used in multichannel wavelength conversion techniques, especially in high bit-rate systems. So, DPSK signals will be more advantageous in future all-optical backbones for both transmission and wavelength conversion, especially in long haul and high bit-rate systems.

4. Conclusion

In this paper, we numerically investigate multichannel wavelength conversion for amplitude modulated signals, phase modulated signals, mixed amplitude and phase modulated signals. We also briefly investigate SBS suppression techniques for achieving a high wavelength conversion efficiency together with the influence of the pump phase modulation on the idler performance. Our simulation results show that DPSK signals are more appropriate for multichannel wavelength conversion because OOK signals will suffer from the inevitable data-pattern-dependent pump depletion. When the modulation format is partially upgraded from amplitude-modulated signals to phase-modulated signals, the DPSK idlers will be greatly affected by OOK signals and this degradation influence becomes more serious when the number of OOK channels is increased.

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