Dual correlated pumping scheme for phase noise preservation in all-optical wavelength conversion

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Abstract: We study the effect of transfer of phase noise in different four wave mixing schemes using a coherent phase noise measurement technique. The nature of phase noise transfer from the pump to the generated wavelengths is shown to be independent of the type of phase noise ($1/f$ or white noise frequency components). We then propose a novel scheme using dual correlated pumps to prevent the increase in phase noise in the conjugate wavelengths. The proposed scheme is experimentally verified by the all-optical wavelength conversion of a DQPSK signal at 10.7 GBaud.

OCIS codes: (190.0190) Nonlinear optics; (190.4380) Nonlinear optics, four-wave mixing.

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1. Introduction

Future generation optical communication networks which employ high speed all-optical signal processing will require advanced devices and subsystems [1]. All-optical wavelength conversion schemes enable the implementation of optically transparent wavelength conversion at communication nodes. All-optical wavelength conversion also reduces the blocking probability in wavelength routed optical networks [2]. Different methods have been used in the past to perform all-optical wavelength conversion. The use of four-wave mixing (FWM) nonlinearity is attracting attention because of its transparency to bit rate and modulation format. All-optical wavelength conversion techniques using FWM have been demonstrated with greater than 100% efficiency for a wavelength detuning of 10 nm and with polarization insensitivity [3–7]. Transparency to modulation format is particularly relevant in the current scenario where the commercial optical communication systems are evolving to advanced modulation formats for enhanced spectral efficiency [8]. In systems that encode information on the phase of the optical carrier, the

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phase noise of the laser is an important parameter that decides the signal quality. When employing FWM to carry out wavelength conversion of data in advanced modulation formats, it is vital to understand the transfer of phase noise from pump and signal to the converted wavelength in order to determine any system impairments caused by the wavelength conversion process.

It has been shown both theoretically and experimentally that FWM results in an increase in phase noise in the converted wavelength [9]. Several schemes have been suggested to prevent the increase in linewidth during FWM. One approach involves modulating the pump with binary phase shift keying [10, 11], while another approach is to dither the two pumps in opposite sign of phase [12–15]. In addition to these, synchronous phase modulation of the pump and signal is utilized in [16, 17]. All the above schemes indirectly rely on producing a specific phase shift between the mixing pumps. In a related work, it has been recently shown that the linewidth broadening during comb-generation can be prevented when the seed frequencies have correlated phase noise [18]. However, using injection-locking as a mechanism to correlate the phase noise of the two seed frequencies is difficult to implement in a practical system, as there is a finite wavelength locking range achievable between the master and slave lasers.

In this paper, we propose a dual correlated pumping scheme which ensures that the wavelength converted signal retains the phase noise of only the original data signal. The proposed scheme does not demand any stringent phase relationship between the pump and the signal, and does not require a pump with extremely low optical phase noise. The supporting mathematical theory is detailed, with the corresponding experimental results. We prove that the phase noise relationship between the mixing waves and the generated waves is independent of the type of phase noise (frequency dependent/independent). The experimental validation of the proposed scheme is presented using a coherent technique detailed in Section 2. All-optical wavelength conversion experiments are carried out with 10.7 GBaud DQPSK modulation, to understand the effect of this phase noise transfer on the system performance of the generated wavelengths. The dual correlated pumping scheme is compared with a single pumping scheme. We experimentally prove that there is no additional penalty due to wavelength conversion in the newly proposed scheme. The details of these experimental results are presented in Section 3.

2. Phase noise due to four-wave mixing

2.1. Theory

Four-wave mixing is a third-order nonlinear process where the mixing frequencies, pump (ω_{pump}) and the signal (ω_{signal}) generate two additional frequencies, $\omega_{Stokes} = 2\omega_{pump} - \omega_{signal}$ and $\omega_{anti-Stokes} = 2\omega_{signal} - \omega_{pump}$ in a partially-degenerate scheme given in Fig. 1(a). In the non-degenerate scheme given in Fig. 1(b,c), the mixing frequencies pump-1 (ω_{pump-1}), pump-2 (ω_{pump-2}) and signal (ω_{signal}) generate multiple additional frequency components. We consider two of them relevant to this study - $\omega_{Stokes} = \omega_{pump-1} + \omega_{pump-2} - \omega_{signal}$ and $\omega_{anti-Stokes} = \omega_{pump-2} + \omega_{signal} - \omega_{pump-1}$. In the non-degenerate scheme, only the conjugates that are of interest to us (with respect to the phase noise/linewidth study) are studied and mentioned henceforth. The mixing frequencies are unevenly separated so that the generated frequencies are distinguishable from the pumps and the signal.

The spectral broadening of the generated wavelengths in FWM was first reported by K. O. Hill in [20] and later studied in detail in [9]. In those studies, the phase noise of the laser was quantified through its linewidth ($\Delta\omega$). However, coherent techniques have enabled the direct measurement of the phase error variance ($\sigma^2_{\Delta\theta}$) [21, 22]. In addition to white noise, laser phase noise has a frequency dependent contribution that predominantly follows a $1/f$ dependence [21–23]. When the contribution due to white noise is pre-dominant over $1/f$ noise, $\Delta\omega$ and $\sigma^2_{\Delta\theta}$ follow a linear relation [9]. Thus the relation between the linewidths of the generated waves and the mixing waves are identical to those between their phase error variances. For the

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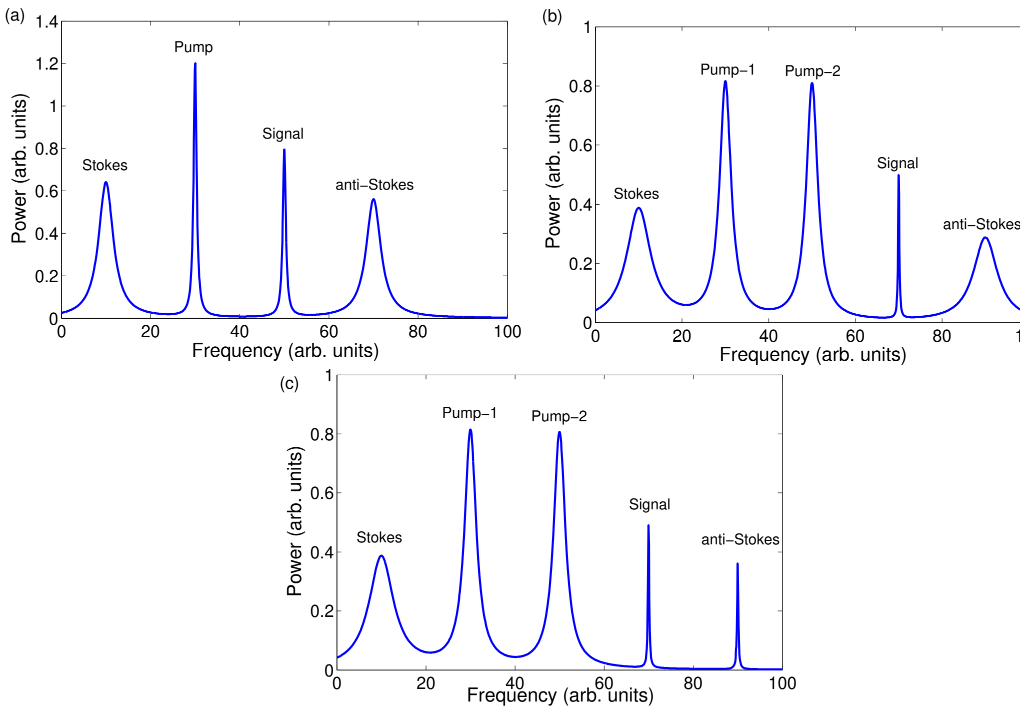

Fig. 1. Spectral representation of (a) Partially-degenerate scheme, (b) Non-degenerate scheme with the two pumps without correlated phase noise, (c) Non-degenerate scheme with the two pumps having correlated phase noise.

partially-degenerate case and where $\omega_{signal} > \omega_{pump}$ (Fig. 1(a)), the linewidth of the generated wavelengths are related to those of the pump and signal as,

$$\Delta\omega_{anti-Stokes} = 4\Delta\omega_{signal} + \Delta\omega_{pump}, \tag{1}$$

$$\Delta\omega_{Stokes} = 4\Delta\omega_{pump} + \Delta\omega_{signal}. \tag{2}$$

For the case when $\omega_{signal} < \omega_{pump}$, the above phase noise relations for the Stokes and the anti-Stokes frequencies are interchanged. In the case of non-degenerate FWM (Fig. 1(b)), the linewidth relation for the Stokes and anti-Stokes components is given as,

$$\Delta\omega_{anti-Stokes/Stokes} = \Delta\omega_{signal} + \Delta\omega_{pump-1} + \Delta\omega_{pump-2}. \tag{3}$$

When the two pumps in the non-degenerate scheme are correlated (Fig. 1(c)), we derive the following relation,

$$\Delta\omega_{anti-Stokes} = \Delta\omega_{signal}, \tag{4}$$

$$\Delta\omega_{Stokes} = 4\Delta\omega_{pump-1/2} + \Delta\omega_{signal}. \tag{5}$$

It is observed from Eq. (4), that the anti-Stokes component retains the linewidth and hence, the phase noise of the signal. As mentioned earlier, these relations are true for phase noise and linewidth in the case where the white noise is dominant over the $1/f$ noise. When the

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$1/f$ noise is dominant, the relationship between the phase error variance and the linewidth is quadratic [24]. The corresponding linewidth relationships are derived in Appendix A. It must be noted that the relations discussed in this section are true for FWM in any nonlinear medium. The following section describes the experimental setup used to verify the proposed scheme of phase-noise retention using a dual correlated pumping scheme.

2.2. *Experimental setup*

The schematic of the experimental setup used to measure the power spectral density of the FM noise of the different components due to FWM is shown in Fig. 2. For the partially-degenerate scheme, light from two laser sources (Laser-1 and Laser-2) is combined using a 3 dB coupler and passed through an isolator (ISO) and semiconductor optical amplifier (SOA), where the two frequencies undergo partially-degenerate FWM. For the non-degenerate scheme with correlated pumps, light from two lasers (Laser-1 and Laser-2) are combined using a 3-dB coupler, passed through an optical isolator (ISO) and mixed in an SOA, where the three frequencies undergo non-degenerate FWM. A carrier suppressed amplitude modulation of Laser-1 at 25 GHz is used to generate correlated pumps with a frequency separation of 50 GHz [25]. The filtering stage (Filter) consists of two optical band-pass filters with bandwidths of 30 GHz and two EDFAs to overcome filtering losses. The 90/10 coupler splits the light, where 90 percent is given to the linewidth measurement system and 10 percent is used for monitoring the spectrum with an optical spectrum analyzer (OSA). The linewidth measurement set-up consists of delayed self-heterodyne section and a real time oscilloscope used for coherent off-line signal processing of down-converted optical signal, as detailed in [22].

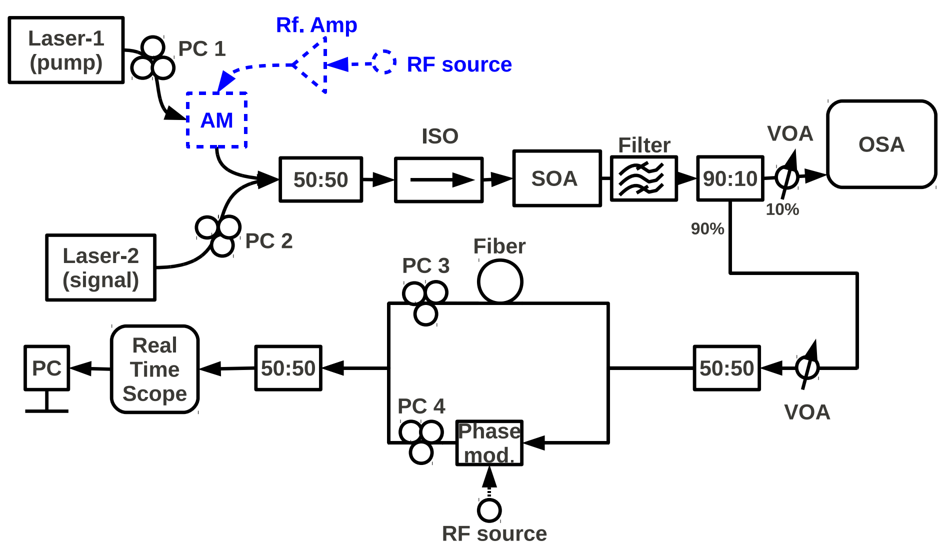

Fig. 2. Schematic of the experimental setup for linewidth measurement of four-wave mixing components, for different schemes. (Blue dashed) Non-degenerate scheme with correlated pumps.

2.3. *Results and Discussions*

The Stokes and the anti-Stokes frequencies are filtered and their linewidths are measured for the partially-degenerate scheme using the self-heterodyne phase-modulation detection technique detailed in [22]. This experiment is repeated for different values of linewidths of the signal. The linewidth of the signal (external cavity laser (ECL)) can be modified by changing the operating power of the laser [26]. The measured linewidths for the Stokes and the anti-Stokes component for different values of linewidths of the signal, for the partially-degenerate scheme are shown in Fig. 3(a). The signal linewidth is varied from 15 kHz to 80 kHz while that of the pump (extended cavity semiconductor laser (ECSL)) is kept constant at approximately 30 kHz [27]. The Stokes linewidth is found to vary from approximately 120 kHz to 165 kHz, and that of anti-Stokes is found to vary from approximately 70 kHz to 325 kHz. The solid line in this figure shows the expected linewidth values for the Stokes and antiStokes components calculated using Eq. (1) and Eq. (2). It is observed from Fig. 3(a) that the experimentally measured linewidth values closely follow the theoretical predictions.

Figure 3(b) represents power spectral density (PSD) of the FM noise of different FWM components for the partially-degenerate scheme. The phase error variance relations corresponding to the linewidth relations detailed in Eq. (1) and Eq. (2) are used to obtain the expected PSD of the FM noise, shown as solid lines in Fig. 3(b). The PSD of the FM noise gives the PSD of instantaneous frequency fluctuations [21, 22]. Hence, it completely describes the $1/f$ noise and white noise contributions to the phase noise. It is observed from Fig. 3(b) that, the FWM phase noise relationship is satisfied at all the frequencies, implying that the phase error variance relationship (which is same as the linewidth relationship given in Eq. (1) and Eq. (2)) is true for white noise and $1/f$ phase noise. Although it is not shown here, we also verified through independent experiments that this phase noise relationship is independent of the separation between the mixing frequencies and amplified spontaneous emission of the SOA.

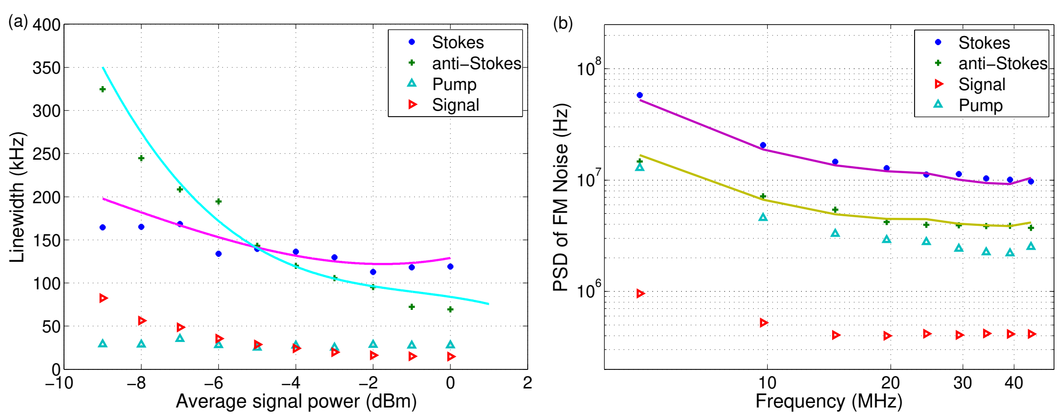

Fig. 3. (a) Linewidth measurement results of FWM components for partially-degenerate scheme, where the linewidth of the signal is varied by changing its power, (b) Power spectral density (PSD) of the FM noise of different four-wave mixing components, at low frequency ($1/f$ noise) region (average signal power of -2 dBm).

The linewidth and FM noise characteristics of the two pumps (pump-1 and pump-2), signal, Stokes and anti-Stokes components are now measured for the dual correlated pumping scheme. The linewidth and FM noise characteristics of pump-1 and pump-2 (here, this is a modulated grating Y-branch laser (MGY)) shown in Fig. 4 are found to be identical since they are derived from the same laser source using the carrier suppressed amplitude modulation scheme. The linewidth measured for the different FWM components for different values of linewidths of the signal, in the dual correlated pumping scheme, are shown in Fig. 4(a). The signal (here, a distributed feedback laser (DFB) [28]) linewidth is varied from 350 kHz to 690 kHz while that of the correlated pumps (pump-1 and pump-2 in Fig. 4) are approximately 8 MHz. The anti-Stokes

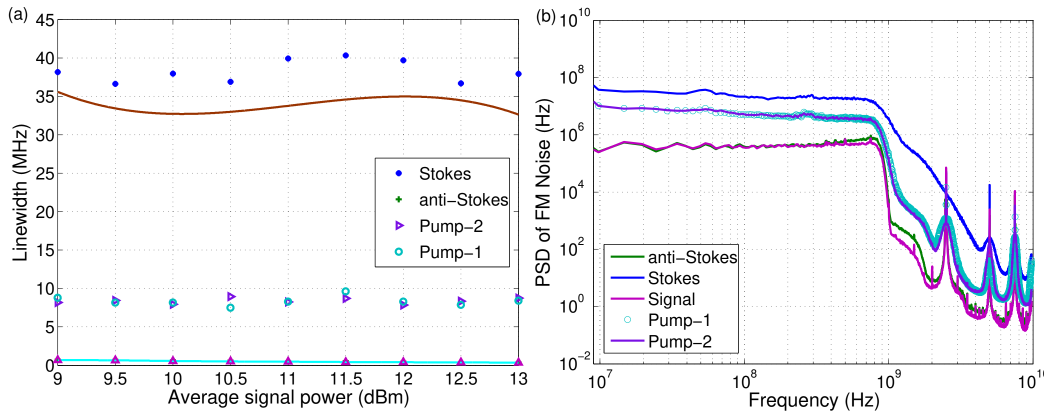

Fig. 4. (a) Linewidth measured for the pumps and signal for a non-degenerate FWM scheme with correlated pumps having linewidth of 8 MHz. The signal linewidth is varied from 350 kHz to 690 kHz, (b) Power spectral density (PSD) of the FM noise of different four-wave mixing components for dual correlated pumping scheme (average signal power of -9.5 dBm).

linewidth remains at the same value of the signal linewidth in each case for the correlated dual pump case, but the linewidth of the Stokes is found to vary from 36 MHz to 40 MHz. The expected results obtained using Eq. (4) and Eq. (5) are shown as solid lines. It is observed that the linewidth of the anti-Stokes component is identical to that of the signal, while that of the Stokes is larger than the signal, as predicted by Eq. (4) and Eq. (5) respectively. Figure 4(b) shows the corresponding PSD of the FM noise of different FWM components, for the dual correlated pumping scheme. It can be observed in Fig. 4(b) that the anti-Stokes component retains the phase noise of the signal, at all frequencies. Thus, it is experimentally verified that, in the dual correlated pumping scheme, the phase noise of the anti-Stokes component is independent of the phase noise of the pump. The impact of this result is further explored by performing all-optical wavelength conversion using FWM in an SOA on a 10.7 GBaud DQPSK data signal, with the suggested scheme.

3. All-optical wavelength conversion studies

All-optical wavelength conversion of 10.7 GBaud DQPSK data using FWM in SOA is carried out to understand the effect of the phase noise transfer during wavelength conversion for different FWM schemes and to show how this phase noise transfer affects the system performance. The partially degenerate pumping scheme is initially tested using pump lasers with different phase noise values. The pump with the largest phase noise is further used for generating correlated pumps to demonstrate the effectiveness of the proposed dual correlated pumping scheme.

3.1. Experimental setup

The experimental setup in Fig. 5 is used for all-optical wavelength conversion studies of 10.7 GBaud data using FWM. Light from two laser sources, Laser-1 and Laser-2, is combined using a 3 dB coupler and passed through an isolator (ISO) before it undergoes FWM in the SOA. Laser-2 is modulated using an IQ modulator to generate 10.7 GBaud DQPSK data. Data-1 and Data-2 from the signal generator are delayed using a coaxial RF delay line to de-correlate the data signals before applying them to the IQ modulator, which is appropriately biased. The operating conditions of the SOA are optimized to obtain 100 percent conversion efficiency (ratio

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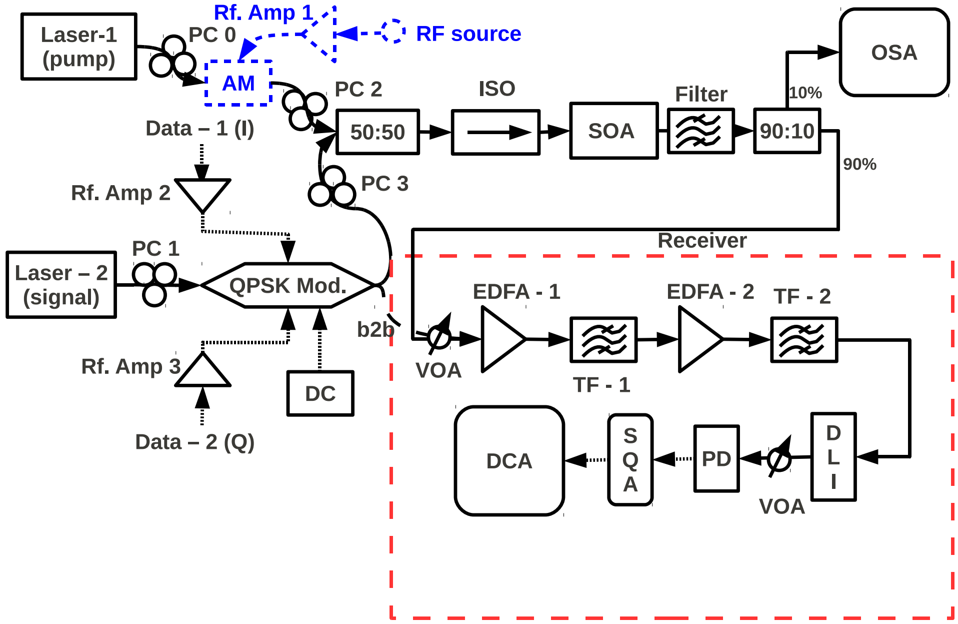

Fig. 5. Schematic of the experimental setup to measure BER as a function of received power. The portion of the setup in dashed blue is used for non-degenerate scheme, and correlated pumps. PD - Photodetector, SQA - Signal Quality Analyzer, DCA - Digital Communications Analyzer.

of output conjugate power and input signal power) for wavelength conversion [7]. The filtering stage consists of two optical band-pass filters with bandwidths of 30 GHz and two EDFAs. The filtered FWM component is passed to a 90/10 coupler, with 10 percent of the signal power used to observe the filtered spectrum in an OSA and the 90 percent of the signal power passed to the receiver stage. The receiver stage consists of two amplifiers (EDFA-1 and EDFA-2) and two filters (TF-1 and TF-2). The filters are used for removing out-of-band ASE. The variable optical attenuator (VOA) is used for changing the received power and hence the OSNR. The output of TF-2 is demodulated using a delay line interferometer (DLI) and the DLI output is fed to the signal quality analyzer (SQA) to determine the bit error rate (BER) of the received signal. For implementing the dual correlated scheme, the correlated pumps with a frequency separation of 50 GHz are generated using carrier suppressed amplitude modulation of Laser - 1, at 25 GHz. The frequency separation between the correlated pumps and the signal is adjusted such that the generated Stokes and anti-Stokes components are distinguishable from the pumps and the signal. Figure 6 shows the input spectrum (dotted line) before FWM and the spectrum at the ouptut of SOA (continuous line).

Figure 6 clearly indicates the generation of additional frequency components due to FWM in the SOA. The Stokes wavelength with the larger phase noise and the anti-Stokes output which is expected to retain the phase noise of the signal are indicated in this diagram.

3.2. Results and discussion

The measured BER values for different received powers of the signal (measured back-to-back), Stokes and the anti-Stokes components for the partially-degenerate FWM scheme are given in Fig. 7. I and Q channels are demodulated one at a time and since the BER is verified to be identical for both the I and Q channels, the results presented here are those corresponding

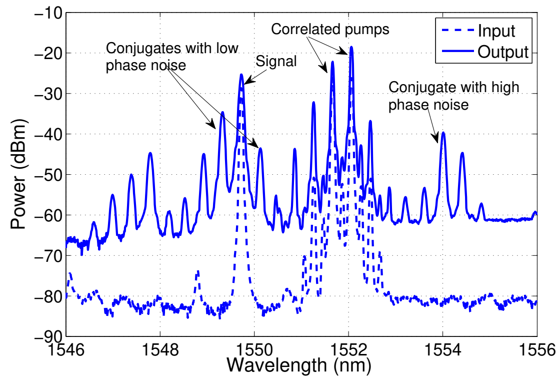

Fig. 6. Spectra at the input (dotted line) and output (continuous line) of SOA, when correlated pumps are used.

to one of the channels. The laser (Laser-2) used to generate the DQPSK signal is a DFB laser with a linewidth of approximately 700 kHz. This experiment is carried out using pump lasers of different linewidths, with $\omega_{signal} > \omega_{pump}$ in all the cases. The pump used in the first experiment is an ECSL (linewidth of 60 kHz), and that in the second experiment is a wavelength-tunable MGY (linewidth of $\sim$ 5 MHz) [29]. The linewidth of the MGY laser is observed to change with wavelength as different current values are applied to the different laser sections to change the wavelength of operation. To increase the linewidth, the MGY laser is tuned from ITU-T grid Channel 40 (5 MHz linewidth) to Channel 38 (8 MHz linewidth). When the linewidth of the pump is increased a penalty is observed for the Stokes component as expected. It is also observed that the pump with a larger phase noise results in an error floor for the Stokes component. The error floor increases from 1e-6 to 1e-5 when the pump linewidth is changed from 5 MHz to 8 MHz, whereas error-free performance (BER lower than 1e-9) is obtained when pump with a linewidth of 60 kHz is used.

The dual correlated pumping scheme is tested next with the tunable MGY laser operated at a linewidth of 8 MHz employed as the pump laser. The signal at the input, the signal through SOA, Stokes and the anti-Stokes component are filtered independently and their BER characteristics are shown as a function of received power in Fig. 8. It is observed that the BER of the anti-Stokes component is identical to that of the signal. The BER corresponding to the Stokes component is found to result in an error floor of approximately 1e-4. These BER results are as expected from the phase noise transfer as outlined by the theoretical predictions of Eq. (4) and Eq. (5) in section 2. Thus, it is experimentally verified that in this proposed FWM scheme using dual correlated pumps, the phase noise from the pump is not transferred to the generated wavelength, irrespective of the type of phase noise (frequency dependent/independent), and the wavelength conversion can be undertaken without a performance degradation.

Ensuring that the wavelength converted signal retains the phase noise of the original data signal is an important aspect in an optical network that employs coherent transmission for enhanced spectral efficiency, because it gives the freedom to choose the “local” pump laser with an arbitrary phase noise. It also prevents accumulation of phase noise when data is transferred through the nodes of an optical network where multiple optical wavelength conversions may be required to avoid contention. In addition, in practical optical-wavelength conversion experiments, stimulated Brillouin scattering (SBS) is one of the impeding factors that prevents power scaling in FWM. The linewidth of the pump lasers are typically broadened to increase the SBS threshold [19], however this would significantly degrade system performance if standard FWM

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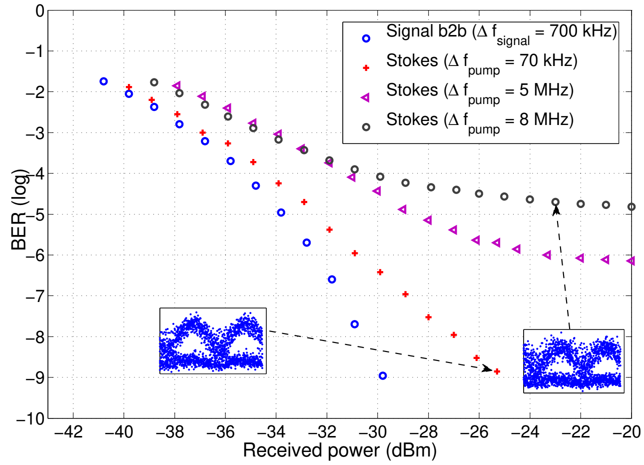

Fig. 7. BER as a function of received power for DQPSK data format using DFB laser as signal (having linewidth of approximately 700 kHz) and ECSL or MGY laser as pump. MGY laser used for this experiment is operated at a linewidth of 5 MHz (Ch - 40) and 8 MHz (Ch - 38). Eye diagrams at certain BER values are included in the figure.

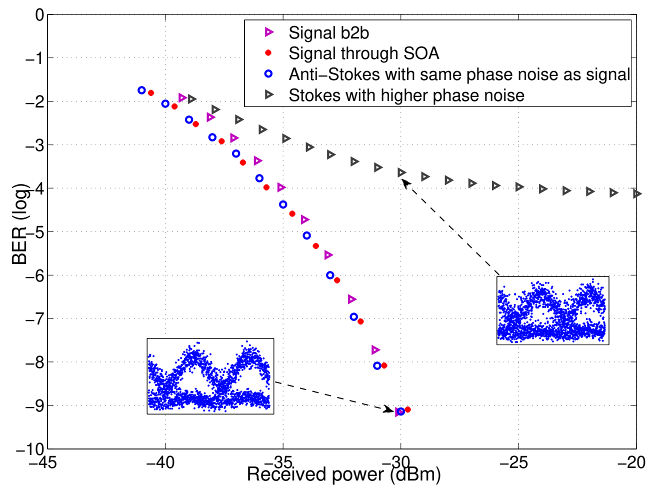

Fig. 8. BER as a function of received power in the non-degenerate FWM scheme using dual correlated pumps (each of linewidth 8 MHz) and signal (700 kHz linewidth). Eye diagrams at certain BER values are included in the figure.

techniques are employed in conjunction with advanced modulation format transmission. In the proposed scheme, the pump with the broadened linewidth does not lead to a degradation of signal quality in the wavelength converted signal. The experimental technique demonstrated in this paper is just one method to generate two pumps with correlated phase noise. For example, any two wavelengths from an optical frequency comb with a large spectral bandwidth, as outlined in [30], can be used with a programmable optical bandpass filter to obtain the two pumps with correlated phase noise, and a wide wavelength conversion range can be achieved by selecting different pairs of modes using the programmable optical bandpass filter.

4. Conclusion

Phase noise transfer from the mixing frequencies to the generated frequencies is studied for different FWM schemes. The phase noise of the generated frequencies is typically larger than that of the mixing frequencies. We propose and experimentally demonstrate a dual correlated pumping scheme, where the phase noise of the converted wavelength is identical to that of the signal and is independent of the phase noise of the pump. All-optical wavelength conversion of 10.7 GBaud DQPSK signal is carried out and the effectiveness of the new scheme is demonstrated. This result could prove to be invaluable if all-optical wavelength conversion is to be deployed in commercial communication systems that use advanced modulation formats.

5. Appendix A

The spectral representations for the partially degenerate and the non-degenerate FWM schemes are shown in Fig. 1(a) and Fig. 1(b,c) respectively. The linewidth relationship for the partially degenerate scheme is derived from first principles in [9, 31] and that for the non-degenerate scheme is given in [32]. Here we derive the linewidth relationship of the anti-Stokes and the Stokes components for the non-degenerate FWM scheme when the two pumps have correlated phase noise.

Consider the non-degenerate scheme represented in Fig. 1(c), where the signal and the two pumps have an unequal frequency separation between them. The absolute phase, θ, of the different FWM components are related as,

$$\theta_{anti-Stokes} = \theta_{signal} + \theta_{pump-2} - \theta_{pump-1}, \tag{6}$$

$$\theta_{Stokes} = \theta_{pump-1} + \theta_{pump-2} - \theta_{signal}. \tag{7}$$

When the two pump sources have correlated phase noise, then the phase relationship between them is given by,

$$\theta_{pump-2} = \theta_{pump-1} + \theta_0, \tag{8}$$

where θ_0 is an arbitrary constant that represents the phase offset between the two pumps. The fluctuation in phase ($\Delta\theta$) is a random variable whose variance (defined as the phase error variance, $\sigma^2_{\Delta\theta}$) is used for quantifying the phase noise [21].

Following the methodology in [9, 31] and [32], and using the general relationship for phase error variance, it can be shown that,

$$\sigma^2_{\Delta\theta-Stokes} = \sigma^2_{\Delta\theta-signal} + \sigma^2_{\Delta\theta-pump-2} + \sigma^2_{\Delta\theta-pump-1} - 2\mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-1})$$

$$-2\mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-2}) + 2\mathrm{Cov}(\Delta\theta_{pump-2}, \Delta\theta_{pump-1}), \tag{9}$$

where Cov(x,y) represents the covariance of two random variables, x and y.

When the phase noise of the pump and the signal is un-correlated,

$$\mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-1}) = \mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-2}) = 0, \tag{10}$$

and when the phase noise of the two pumps are correlated,

$$\mathrm{Cov}(\Delta\theta_{pump-2}, \Delta\theta_{pump-1}) = \sigma^2_{\Delta\theta-pump-2} = \sigma^2_{\Delta\theta-pump-1}. \tag{11}$$

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Hence the phase error variance of the Stokes component is given by,

$$\sigma^2_{\Delta\theta-Stokes} = \sigma^2_{\Delta\theta-signal} + 4\sigma^2_{\Delta\theta-pump-1/2}. \tag{12}$$

Laser phase noise has contributions due to white noise and $1/f$ noise [23]. When the laser phase noise is dominated by white noise, the phase error variance ($\sigma^2_{\Delta\theta}$) is linearly related to the linewidth ($\Delta\omega$) [21]. Thus, the corresponding linewidth of the Stokes component is given by,

$$\Delta\omega_{Stokes} = 4\Delta\omega_{pump-1/2} + \Delta\omega_{signal}. \tag{13}$$

Eq. (13) indicates that the phase noise of the Stokes component increases and the increase is the same as that of the partially degenerate case given in Eq. (2) [9, 31].

When the two mixing pumps in the non-degenerate scheme have correlated phase noise, the phase error variances of the anti-Stokes component is given by,

$$\sigma^2_{\Delta\theta-anti-Stokes} = \sigma^2_{\Delta\theta-signal} + \sigma^2_{\Delta\theta-pump-2} + \sigma^2_{\Delta\theta-pump-1} - 2\mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-1})$$

$$+2\mathrm{Cov}(\Delta\theta_{signal}, \Delta\theta_{pump-2}) - 2\mathrm{Cov}(\Delta\theta_{pump-2}, \Delta\theta_{pump-1}). \tag{14}$$

Using Eqs. (10) and (11), the phase error variance of the anti-Stokes component is,

$$\sigma^2_{\Delta\theta-anti-Stokes} = \sigma^2_{\Delta\theta-signal}. \tag{15}$$

The corresponding linewidth relationship is,

$$\Delta\omega_{anti-Stokes} = \Delta\omega_{signal}. \tag{16}$$

Thus, the dual-correlated pumping scheme retains the phase noise of the signal in the anti-Stokes component. It has been shown experimentally that a correlated phase noise between the signal and the pump leads to frequency comb generation without an increase in phase noise [18]. The procedure detailed in this Appendix can be used to theoretically validate that result.

When the laser phase noise is dominated by $1/f$ noise, Eq. (1) - Eq. (5) hold true for the phase error variance, but not for the linewidths.Thus the corresponding linewidth relationship for the partially-degenerate scheme represented in Fig. 1(a) becomes,

$$\Delta\omega^2_{anti-Stokes} = 4\Delta\omega^2_{signal} + \Delta\omega^2_{pump}, \tag{17}$$

$$\Delta\omega^2_{Stokes} = 4\Delta\omega^2_{pump} + \Delta\omega^2_{signal}. \tag{18}$$

The linewidth relationships for other FWM schemes change similarly, whenever the laser phase noise is dominated by $1/f$ noise.

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