Comparison of frequency symmetric signal generation from a BPSK input using fibre and semiconductor based non-linear elements

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Abstract—**We compare two nonlinear media for simultaneous carrier recovery and generation of frequency symmetric signals from a 42.7Gbit/s nonreturn-to-zero binary phase shift keyed (NRZ-BPSK) input by exploiting four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) and a highly nonlinear fibre (HNLF) for use in a phase sensitive amplifier.**

***Index Terms*— Nonlinear optics, four-wave mixing, All-optical networks, Optical communications, injection-locked lasers**

I. Introduction

Phase sensitive amplifiers (PSA) are expected to contribute significantly in extending the transparent length of future transmission links [1]. This is because of two main capabilities that PSAs are able to offer. As linear elements, PSAs have the potential for noise figures which are lower than the 3 dB quantum limit of conventional phase insensitive amplifiers (PIAs) [1],[2]. As nonlinear elements, PSAs may provide simultaneous phase and amplitude regeneration capabilities which are useful for all-optical regeneration of phase encoded signals [3]. Significant progress has been made worldwide to demonstrate the performance of parametric amplification using various schemes [3],[4]. Such a PSA should incorporate circuits that enable the phase synchronization of local pumps to the incoming signal. The various implementations of non-degenerate PSA's also clearly require the generation of phase locked pumps appropriately detuned in frequency from the incoming signal. Optical injection locking and/or optical phase locked loops [5] might provide solutions for achieving the phase synchronization. However, both are challenging if a carrier-less BPSK is used. Therefore, to enable parametric amplification of BPSK signals a modulation stripping process is needed, to generate a carrier that will be used as a reference to phase lock the pump waves. We have recently reported a configuration based on FWM which simultaneously provides modulation stripping and the generation of appropriately spaced pumps [6]. In this paper we compare two nonlinear media for generation of frequency symmetric signals with the correct phase from an incoming 42.7Gbit/s BPSK signal, using a FWM process together with injection locking.

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II. Principle of Operation

A NRZ-BPSK signal with an amplitude, frequency, and phase of E_s, ω_s, and φ_s, respectively, and a CW pump with parameters E_p, ω_p, and φ_p can be simultaneously input to a nonlinear medium in order to excite FWM. The FWM process will generate two (or more) idlers waves nearest to the signal and pump as shown below:

$$E_{i1} = E_s^2 . E_p^* . e^{i((2\omega_s - \omega_p)t - (2\varphi_s - \varphi_p))} \quad (1)$$

$$E_{i2} = E_p^2 . E_s^* . e^{i((2\omega_p - \omega_s)t - (2\varphi_p - \varphi_s))} \quad (2)$$

where E_{i1} and E_{i2} are the electric fields for the two idler waves.

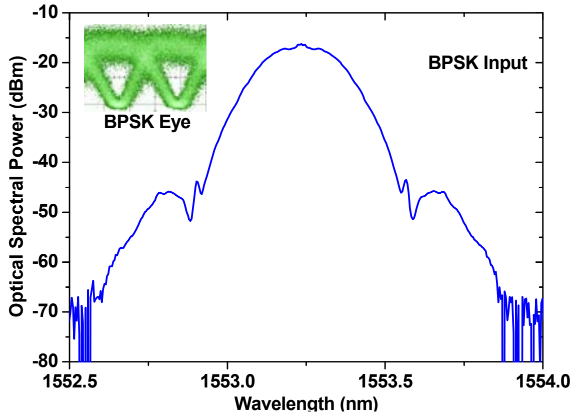

Fig. 1. Input BPSK spectrum and eye diagram (inset)

Fig1 shows the optical spectrum and eye diagram of the 42.7Gbits NRZ-BPSK signal. Ideally, a BPSK-modulated signal consists of {0, π} phase-encoded data. The phase of E_{i1}, φ_{i1}, is shown in (1) to be equal to $2\varphi_s$-φ_p, and by choosing the phase of the cw pump as the reference, i.e. φ_p=0, we see that for an incoming data bit phase (φ_s) equal to 0, φ_{i1} is always equal to 0. Likewise, for each data bit phase equal to π, φ_{i1} is equal to 2π, which is equivalent to 0. In this way, the BPSK modulation is essentially stripped from the idler [6]. The phase of the FWM-generated signal, E_{i1}, is uniquely determined by the signal carrier and pump phase according to ($\varphi_{i1}=2\varphi_s-\varphi_p$) and this idler component (fig 4) was used to injection lock a discrete mode laser (DML) [7].The output from the DML and the original pump are symmetrically spaced frequencies with respect to the input BPSK signal. The frequency and phase relationship in (1) is a condition for the optimal operation of a dual pump PSA configuration [3],[4].

III. Experiment

The experimental setup is shown in Fig.2. A 42.7Gbit/s NRZ-BPSK signal was generated using a DML outputting a wavelength of λ_s=1553.23nm and a linewidth (LW) of 470 kHz. This optical carrier was injected into a Mach-Zhender modulator (MZM) driven by an electrical 2^{31}-1 pseudo-random bit sequence (PRBS) from a pattern generator.

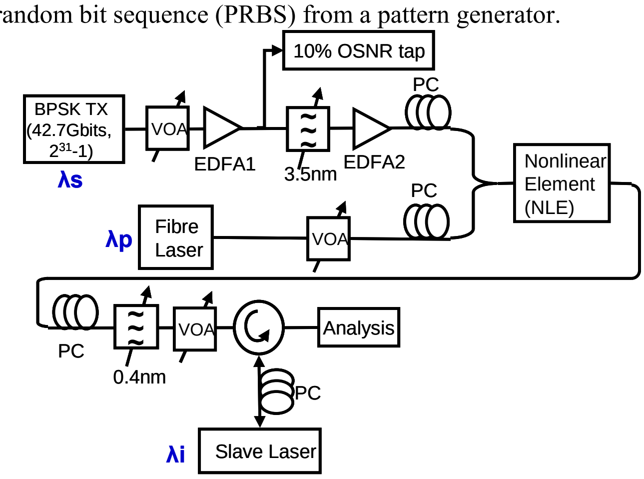

Fig. 2. Experimental implementation for generating a symmetrical pump signal from a BPSK signal for non-degenerate phase-sensitive amplification; PC-polarization controller, VOA-variable optical attenuator, EDFA-erbium doped fibre amplifier

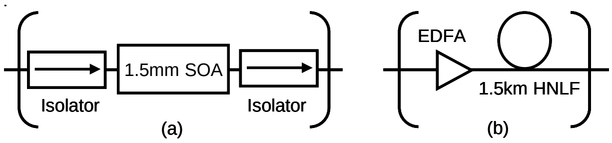

Fig. 3. Nonlinear elements; (a) semiconductor optical amplifier arrangement, (b) highly nonlinear fibre arrangement.

After the BPSK transmitter a variable optical attenuator (VOA) and an erbium-doped fibre amplifier (EDFA) were placed to set the optical signal-to-noise ratio (OSNR). The total optical power was then restored to a fixed level using a second EDFA with an automatic power control mode to set the total power at a constant level, and this signal was coupled with a CW pump from a fibre laser outputting a wavelength of λ_p=1553.65nm with a LW of 5kHz. Both signals were launched into nonlinear elements in order to generate the modulation stripped idler via FWM [8]. Polarization controllers were used to align the signals and so maximize the FWM process. In the case of the SOA nonlinear element (NLE), two isolators were connected at the input and output of the SOA to eliminate back reflections (Fig 3a). The SOA had a 20dB small-signal gain at the 200mA operating bias current.

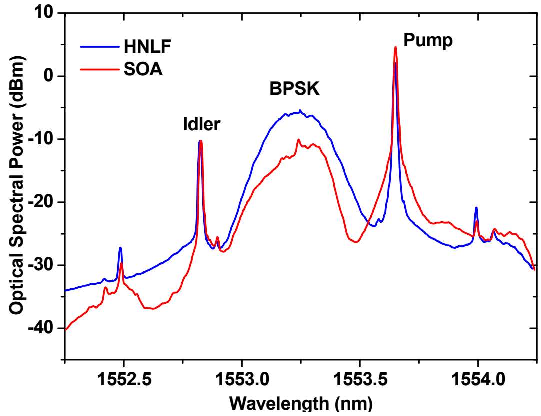

Fig. 4. FWM Spectra at the output of SOA (red) and HNLF (blue).

The device was 0.1μm thick, 1500μm long, and had a saturated optical power output of 15dBm.The SOA and two isolators were then replaced by a HNLF with a zero-dispersion wavelength at 1554nm, a nonlinear coefficient of 18 $(W.km)^{-1}$, a 1.5km length, a dispersion slope of 0.046ps/nm/km^2, an effective area of 12μm^2, and a loss of 1.3dB/km at 1550nm (Fig 3b). It was necessary to add an in-line EDFA to ensure an identical idler power. In both cases, pump and signal powers & polarization were optimized to give an idler power at the NLE output of -10dBm when the input OSNR of the signal was >32dB and a 50GHz frequency spacing between the signal and the pump (Fig 4).

In these experiments, the maximum power of the idler was limited either by the stimulated brillouin scattering (SBS) threshold of the HNLF or the gain saturation of the SOA. The idler (λ_i=1552.81nm) component was passed through a ~0.4nm bandwidth tunable filter and a VOA to set the injected power into the slave DML to -21dBm. The injection-locked laser output was observed at the third port of the circulator as shown in Fig. 2. The linewidth was measured using the self-heterodyne technique [9].

IV. Results

The filtered idler signal and the injection locked laser spectra for both cases are shown in Fig. 5. The idler was slightly broadened due to residual BPSK modulation. The LW of the measured idler was 980 kHz and 1.28 MHz for SOA and HNLF schemes, respectively. According to (1), the expected LW was around 1MHz and the SOA modulation stripped idler LW was in agreement with (1). The slight deviation of HNLF scheme idler LW from the expected may be due to SBS.

Using this low power idler, with residual modulation, as a second pump will degrade the performance of the PSA, and so a free running DML (LW= 3.42 MHz) was injection-locked (IL) using this idler component (Fig.5). The measured LW of the output injection locked laser (ILL) was 950 kHz and 1.25 MHZ for SOA and HNLF schemes, respectively. The measured injection locked laser LW for different input OSNR values of both the SOA and HNLF systems shown in Fig.6 and indicates an approximately constant LW for an OSNR >15dB

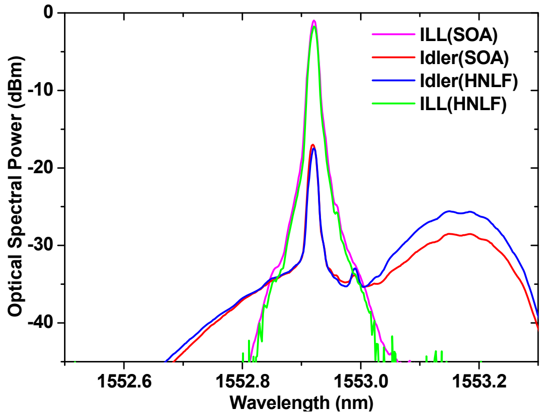

Fig. 5. Optical Spectra of FWM idlers and injection locked DML for SOA and HNLF schemes

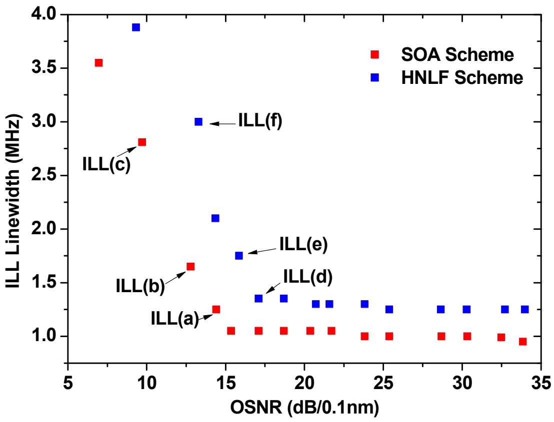

Fig. 6. Measured linewidths for different input OSNR for SOA (red) and HNLF (blue) schemes

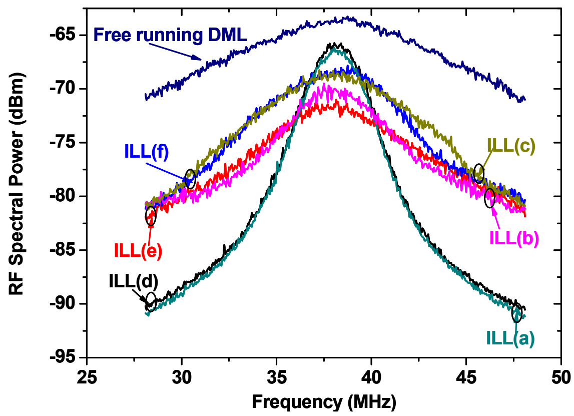

Fig. 7. Measured self heterodyned linewidth for the free-running, and injection-locked DML laser for different OSNR

for the SOA scheme and an OSNR >17dB for HNLF scheme.

For lower BPSK OSNR values, there was a reduction in idler power [according to (1)] and it reduces the IL bandwidth. We believe that SBS and amplified spontaneous emission noise accumulation inside the slave laser at lower OSNRs (<17dB) caused the increase in LW for the HNLF compared to the SOA scheme.

Fig. 7 shows the RF self-heterodyned spectrum of the free-running and IL DML for both the SOA and HNLF systems at 3 different OSNR input levels. The OSNR input levels to the SOA are 14.45, 12.84, and 9.76 dB/0.1nm which are labeled as a, b, and c, respectively, in Fig. 7. The OSNR input levels to the HNLF are 17.07, 15.91, and 13.34 dB/0.1nm and are labeled as e, f, and g, respectively. The results in Fig 7 confirms that the slave laser is injection locked to the extracted carrier as it is following the idler linewidth which is much less than the free running linewidth of the slave laser.

V. Conclusion

In conclusion, we have investigated two nonlinear devices for generating phase-locked symmetric pumps for a PSA. We show that an SOA gives an improved 2dB OSNR tolerance, when compared to HNLF, as well as a 300 kHz linewidth reduction. Furthermore, due to the short length of the SOA, the phase of the second pump will be preserved, which is not the case for the much longer HNLF. The SOA also can potentially be monolithically integrated into the system as a gain medium. However, the FWM efficiency in SOAs reduces dramatically with increasing data-pump spacing [8], and so will be inappropriate for systems which require large pump spacings (greater than 100GHz).

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