FOUR-WAVE MIXING APLICATION IN SEMICONDUCTOR OPTICAL AMPLIFIER

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Summary Four-wave mixing (FWM) in semiconductor optical amplifiers is an attractive mechanism for wavelength conversion in wavelength-division multiplexed (WDM) systems since it provides modulation format and bit rate transparency over wide tuning ranges. A series of systems experiments evaluating several aspects of the performance of these devices at bit rates of 2.5 and 10 Gb/s are presented.

1. INTRODUCTION

As new applications for telecommunications mature, such as HDTV, multimedia services, and the world wide web, greater demand is being placed on the bandwidth of the existing telecommunications systems. Single mode fiber (SMF) installed around the world has the capacity of many Tb/s. Commercial high-speed systems operate in the range of 2.5–10 Gb/s, thus leaving much room for more efficient use of the available fiber bandwidth. Increasing the channel bit rate beyond current levels will prove to be increasingly difficult since the cost of the supporting electronics increases and the achievable transmission distance decreases due to fiber dispersion. Consequently, a world-wide consensus is driving the utilization of wavelength-division multiplexing (WDM) technologies for a more effective use of the available fiber bandwidth [1].

An important element for implementation of WDM systems is a wavelength converter [2], [3]. Many technologies exist for the implementation of wavelength conversion [4]. Optoelectronic, cross-gain saturation [5], and cross-phase saturation [6] wavelength converters are candidate technologies that offer excellent performance, however, they are not transparent to modulation format [7].1 Complete or so-called strict transparency is offered only by ultra-fast wave mixing techniques based on either four-wave mixing (FWM) or difference frequency generation (DFG) [8]. DFG performance has made impressive strides in recent years through use of quasi-phase matching in AlGaAs waveguides [9]. However, the use of quasi-phase matched waveguides mandates a fixed pump wavelength. This, in turn, means that a given input wavelength can be mapped to only one converted wavelength. FWM in optical fibers [10] is limited by this same pump wavelength restriction.

On the other hand, FWM in semiconductor optical amplifiers (SOA's) [11]–[29] is insensitive to phase matching, offering arbitrary wavelength mapping. Offsetting this advantage are disadvantages associated with polarization dependent conversion as well as the required output filtering of spurious wavelengths.

Nonetheless, FWM SOA wavelength converters have demonstrated high bit rate switching between WDM channels [14], [15], [24], dispersion compensation by phase conjugation (or mid-span spectral inversion) [16], [19], timedomain demultiplexing, multiplexing format conversion, wavelength conversion of microwave subcarriers, and also limited signal processing. In particular, optical signal-to-noise ratio (OSNR), once considered the primary obstacle to any progress toward application of these devices has improved dramatically over the last year and further improvements seem likely.

Fig. 1 is a schematic for a typical FWM experimental configuration.

Two copolarized waves are coupled into the SOA. One of the waves, called the pump wave (E_p) with frequency ω_p is typically stronger than the other wave (i.e., the input signal to be converted) called the probe wave E_q with frequency ω_q. Inside the SOA, the copropagating pump and probe waves mix, forming dynamic gain and index gratings in the SOA through the mechanisms of carrier density modulation, carrier heating and spectral hole burning. The pump wave scattering from these gratings generates two waves, one at the probe frequency and one at a new frequency, $\omega_{cs} = 2\omega_p - \omega_q$.

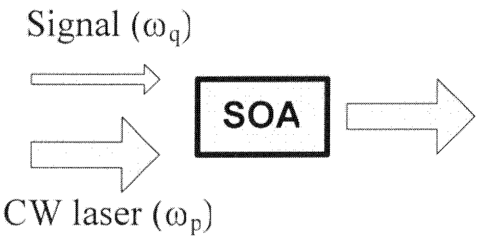

Fig. 1. Schematic configuration for single-pump FWM.

Probe scattering also generates two much weaker waves, one at the pump frequency and one at $\omega_{cs'} = 2\omega_q - \omega_p$. The wave E_{cs} with frequency ω_{cs} is easily shown to be the phase conjugate replica of the original input signal (Fig. 2). As such, it provides the wavelength converted signal. In this paper, we will provide a review of our recent results concerning the application of SOA-based four-wave mixing to wavelength conversion of high bit rate base-band digital optical signals.

A general block diagram for the wavelength converter used in the experiments described below is shown in Fig.3. The converter's optical pump source is a tunable, external cavity diode laser. Its in-fiber output power is about 3 dBm. The pump and probe waves each pass through individual polarization controllers (PC's) before being combined by an 80/20 bidirectional coupler (BDC).

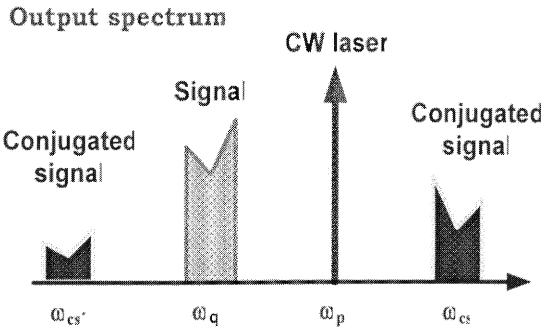

Fig. 2. Typical output FWM sprectrum.

The combined signals are then amplified in a high power erbium-doped fiber amplifier (EDFA), with an output power of about 19 dBm. After amplification, the signals pass through a 10-nm-wide bandpass filter (BPF). As described in [28], [29], this filter increases the OSNR of the converted signal by suppressing the amplified spontaneous emission (ASE) contributed by the high-power EDFA in the spectral region of the converted signal. Following this ASE prefiltering, these signals are coupled into the SOA where FWM generates the converted signal. The SOA is a fiber pigtailed unit from SDL based on a multiquantum-well compressively strained gain medium providing 25-dB fiber to fiber gain. A typical FWM spectral output for this setup is shown in Fig. 2. After mixing in the SOA, the pump and the original signal are suppressed using a 1-nm-wide tunable bandpass filter centered on the converted signal.

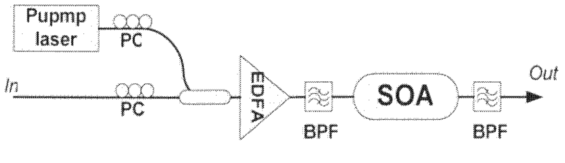

Fig. 3. Schematic of wavelength converter design.

2. SIMULATION RESULT

The most frequently cited figures of merit for FWM wavelength converters are their conversion efficiency and the converted OSNR. The conversion efficiency is defined as the in fiber converted signal power at the SOA output divided by the in-fiber signal power at the SOA input and has been accurately modeled and thoroughly characterized [11]–[13]. However, from a systems perspective, the conversion efficiency is not the primary figure of merit.

By using EDFAs in appropriate positions, it is possible to attain nearly any desired conversion efficiency. The more crucial figure of merit is the OSNR for the converted signal. Its importance is particularly significant to the optimization of a given SOA FWM element for wavelength conversion, because optimum OSNR does not necessarily imply optimum conversion efficiency [20].

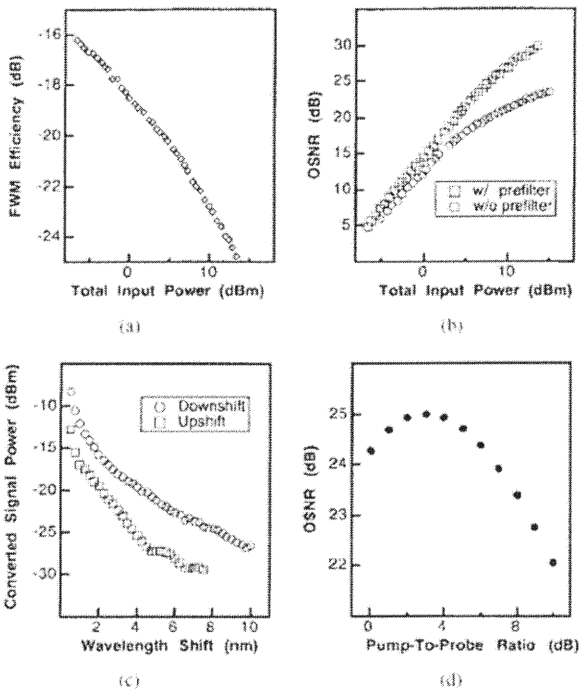

Fig. 4 . (a) Simulated conversion efficiency as a function of the total SOA input power. (b) Simulated OSNR (into 1-Å bandwidth) as a function of the total SOA input power, both with and without an ASE prefilter. (c) Simulated converted signal power as a function of wavelength shift. (d) Predicted OSNR (into 1-Å bandwidth) as a function of the pump-to-probe ratio.

This is true because whereas the amplification intrinsic to the SOA FWM element benefits the conversion efficiency, it also degrades the OSNR through generation of ASE in the converted signal band. This can be seen in Fig. 4(a) and (b) which show measured conversion efficiency and OSNR (wavelength down-shift of 6 nm and 1-Å optical bandwidth) versus the total SOA input power. It can be seen that with increasing input power, and hence increased SOA saturation, conversion efficiency decreases while OSNR steadily rises. As such, it is always better to operate the SOA FWM element in deep saturation to attain maximum OSNR. This will be the case for all experiments described below. Typical total SOA input power levels will be in the range of 12 dBm and will be boosted to this level using the high-power EDFA in Fig. 3. In addition, as described above, an ASE prefilter is used to strip the ASE spectral components generated by this EDFA within the conversion band. This prefiltering typically results in an added 5 dB of OSNR.

Other factors can also influence the magnitude of the OSNR: saturation power, gain, interaction length, and strength of the contributing nonlinear mechanisms. Assuming SOA operation in deep saturation as a given, the OSNR attainable with a fixed SOA structure is then primarily determined by two operating parameters: the wavelength shift and the pump to probe ratio. This dependence is illustrated in Fig. 4(c) and (d). Fig. 4(c) shows the measured converted signal power as a function of the wavelength shift. This wavelength dependence can be understood by modeling the various ultrafast dynamics that contribute to the nonlinear susceptibility function of the amplifier.

In the current experiment, they can be regarded as approximately constant since the total SOA input power is approximately fixed, due to the high level of saturation of the high-power EDFA shown in Fig. 3. As such, the overall roll off in the converted power (and hence efficiency and OSNR) apparent in Fig. 4(c) reflects the superposition of the three response functions in the above equation. In addition, the asymmetry in the up and down conversion response results from partially destructive/constructive phase interference between the contributing FWM mechanisms for wavelength upshifts/downshifts.

The pump-to-probe (P/Q) ratio is important for several reasons. First, since FWM results from a third-order nonlinearity, the theoretically optimum P/Q ratio at constant total power is 3 dB. This is illustrated in Fig. d(d) which shows the predicted OSNR into a 1-Å bandwidth as a function of the P/Q ratio for a wavelength downshift of 16 nm. Second, the P/Q ratio establishes the magnitude of the probe relative to the SOA saturation power. This is true because in deep saturation, the SOA gain saturation characteristic has an effective saturation power that approaches the total input power to the device (in the present case this is approximately the input pump power). As such, the P/Q ratio gives an approximate measure of parasitic gain saturation induced by the input signal. Such parasitic saturation can degrade the converted signal through intersymbol interference (ISI) and chirping that accompanies modulation in the modal gain of the SOA.

3. CONCLUSION

Wavelength conversion by FWM in SOA's is the only method for wavelength conversion that provides both strict transparency and arbitrary wavelength mapping. In this paper, we have provided an update on state-of-the-art results concerning wavelength conversion at high data rates, multichannel conversion and cascaded conversion.

Nonetheless, much progress has been made over the last two years on the issue of OSNR that once was considered the primary impediment to success and this bodes well for further progress on these new fronts.

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