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Experimental demonstration of optical phase conjugation using counter-propagating dual pumped four-wave mixing in semiconductor optical amplifier

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A B S T R A C T

We report optical phase conjugation in C-band by counter-propagating dual pumped non-degenerate four-wave mixing in a semiconductor optical amplifier (SOA). The co-propagating signal and pump waves create a grating inside SOA which diffracts counter-propagating pump and generates the conjugate wave. Since the signal and conjugate waves appear at opposite ends, the conjugate is easily filtered out from the rest of spectrum with minimal spectral shift of the conjugate with respect to the incoming signal. With pump powers of −3.2 dBm each and signal input power of −7 dBm, conjugate power was of −27.2 dBm, giving a conversion efficiency of 1% at 18 GHz pump-signal detuning. By modulating the signal by a periodic pattern ‘1000’ at 10 Gbps using a non-zero chirp intensity modulator and resolving the temporal profile of the electric field envelope of the conjugate wave, we demonstrate spectral inversion.

1. Introduction

Optical phase conjugation (OPC) is used in several applications such as spectroscopy, interferometry, optical squeezing, and optical data processing (see [1] and references therein). In the context of optical fiber communications, OPC is used to mitigate fiber dispersion and nonlinearities by mid-span spectral inversion in which impairments due to fiber dispersion and nonlinearities in the first half of the fiber are inverted by OPC, and compensated by subsequent transmission through the second half of the fiber [2–5].

OPC can be generated in many ways; three-wave mixing in periodically poled $LiNbO_3$, four-wave mixing in fibers and SOAs, and backward stimulated Raman and Brillouin scattering in fibers [1,2,6]. In [7,8], a bidirectional pumping scheme in a SOA to generate OPC was theoretically proposed and the appearance of a signal and conjugate at opposite ends of the SOA was predicted. In [9], a bidirectionally pumped OPC scheme was demonstrated in a SOA using orthogonally polarized counter-propagating pumps of the same wavelength. The orthogonally polarized pumps were used to avoid the reflection of the signal at input port due to the formation of Bragg grating inside SOA, which can lead to difficulty in filtering of conjugate. The signal and conjugate waves appeared at opposite ends of the SOA, also orthogonally polarized. A low conversion efficiency of 0.2% was obtained.

In this paper, we generate OPC in an SOA using counter-propagating dual pumped FWM. Pump_1 and signal waves are injected into one end of the SOA and a second pump is injected into the other end. The beating between pump_1 and signal waves creates a refractive index and gain gratings; the pump_2 senses this grating and scatters, to generate conjugated copy of original signal wave. The conjugate and signal waves appear at opposite ends of the SOA; the conjugate wave is filtered out using an optical filter. With pump and injected signal powers of −3.2 dBm and −7 dBm respectively, the conjugate power was −27.2 dBm giving the higher recorded conversion efficiency of 1% up to 12 GHz pump_1-signal detuning [9]. By modulating the signal wave with a non-zero chirp intensity modulator and resolving the temporal profile of the electric field envelope of the conjugate wave, we demonstrate spectral inversion.

The rest of the paper is organized as follows. In Section 2, we briefly discuss the theory of counter-propagating dual pumped FWM, leading to OPC generation in SOA. The spectrum at the output of SOA shows the generation of desired conjugate as well as additional FWM products. We measure the efficiency of conjugate

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generation as a function of pump-signal frequency detuning and compare it to theoretical values. The temporal resolution of signal and conjugate waves indicates phase inversion. In Section 3, we discuss our experimental setup and results of OPC generation. The spectrum at the output of SOA shows the generation of desired conjugate as well as additional FWM products. We measure the efficiency of conjugate generation as a function of pump-signal frequency detuning and compare it to theoretical values. The temporal resolution of signal and conjugate waves indicates phase inversion. Finally, in Section 4, we conclude by summarizing our results.

2. Theory

Fig. 1 shows the schematic diagram of counter-propagating dual-pumped FWM in SOA. The wavelengths λ_i and frequencies ω_i, $i = 1, 2, 3, 4$ correspond to pump$_1$, pump$_2$, signal and conjugate waves respectively. The pump$_1$ and signal waves are injected into one end of the SOA and pump$_2$ is injected into the other end. Beating between pump$_1$ and signal creates a complex-valued grating – real part corresponds to gain grating and imaginary part corresponds to index grating – in the active layer of the SOA. The origin of the gratings is found in the carrier density pulsation able to sustain modulation at 300 GHz well above its cut-off frequency [7]. The grating diffracts pump$_2$ to create two sidebands at $\omega_2 - \Omega$ and $\omega_2 + \Omega$, where $\Omega = \omega_1 - \omega_3$ is the detuning. The sideband $\omega_2 + \Omega$ corresponds to wavelength λ_4, which is conjugated version of the signal and propagates in the direction opposite to signal. The other sideband $\omega_2 - \Omega$ is the non-conjugate version of signal, denoted by idler$_3$. Conjugate and non-conjugate copies of signal along with the amplified pump$_2$ is present at port 1 as shown in box labelled **A** in Fig. 1. A similar interaction between pump$_2$ and signal waves creates an additional weak grating and is neglected. Other possible FWM interaction is between pump$_1$ and signal, which results in generation of idler$_2$ which is present along with amplified pump$_1$ and signal at port 2 shown in the box **B** of Fig. 1. We summarize different FWM product in Table 1.

The equations governing temporal evolution of signal and generation of conjugate wave can be obtained by substituting the total electric field $E = \sum_{i=1}^{4} A_i(z, t)\exp(j(\omega_i t + (-1)^i k_i z))$ into the nonlinear Schrödinger equation [10] :

$$\nabla^2 E - \frac{n^2}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{1}{\epsilon_0 c^2}\frac{\partial^2 P_{NL}}{\partial t^2}, \tag{1}$$

Table 1
FWM products in dual pumped counter-propagating FWM in SOA.

Interacting waves	FWM product	Comments
ω_1, ω_2, and ω_3	$\omega_2 + \omega_1 - \omega_3$	Conjugate counter-propagating
	$\omega_2 - \omega_1 + \omega_3$	Non-conjugate counter-propagating
ω_1 and ω_3	$2\omega_1 - \omega_3$	FWM product co-propagating

where P_{NL} denotes the induced non-linear polarization. For simplicity of analytical solution we neglected the contribution of idler$_2$ and idler$_3$. Using SOA-FWM analysis outlined in [10], the propagation equation for the forwards and backwards travelling conjugate waves are assuming that the gain saturation is dominated by the pumps:

$$\frac{\partial A_3}{\partial z} = -\alpha_3 A_3 + j\kappa_3 A_4^* \exp(j\Delta k z)$$
$$\frac{\partial A_4^*}{\partial z} = \alpha_4^* A_4^* + j\kappa_4^* A_3 \exp(-j\Delta k z) \tag{2}$$

where $\Delta k = k_1 + k_3 - k_2 - k_4$ is residual phase mismatch and α_3, α_4, κ_3, and κ_4 are given in [10]. These equations are valid for small pump-signal detuning. In our experiments we initially keep the pump-signal detuning to within 10 GHz; The detuning is varied up to 40 GHz to study its effect on FWM conversion efficiency. Solving (2) subject to boundary conditions, $A_3(0) = A_{30}$ and $A_4(L) = 0$, we obtain

$$A_3(z) = A_{30} e^{(\mu-\alpha_3)z}\left[\cos\zeta z + \frac{\zeta\sin\zeta L - \mu\cos\zeta L}{\mu\sin\zeta L + \zeta\cos\zeta L}\sin\zeta z\right]$$
$$A_4(z) = -j\kappa_4 A_{30}^* e^{-(\mu^*-\alpha_4)z}\left[\frac{\sin\zeta(L+z)}{\mu\sin\zeta L + \zeta\cos\zeta L}\right]^* \tag{3}$$

where $\mu = (\alpha_3 + \alpha_4^* + \Delta k)/2$ and $\zeta = \sqrt{(2\mu)^2 - \kappa_3\kappa_4^*}/2$. This shows that $A_4(z)$ is conjugate of A_{30}. The boundary condition for the backwards travelling conjugate is $A_4|_{z=L} = 0$; therefore this backward travelling idler builds up from the right-hand side of (3) which is proportional to the complex conjugate of the input signal A_3. We define conversion efficiency as ratio of output conjugate power at $z=0$ to input signal power at $z=0$, $\eta = \frac{|A_4(0)|^2}{|A_3(0)|^2}$. Putting the value of $|A_3(0)|$ and $|A_4(0)|$ from (3),

$$\eta = \left|\kappa_4 \frac{\sin\zeta L}{\mu\sin\zeta L + \zeta\cos\zeta L}\right|^2 \tag{4}$$

We observe that the conversion efficiency η depends upon

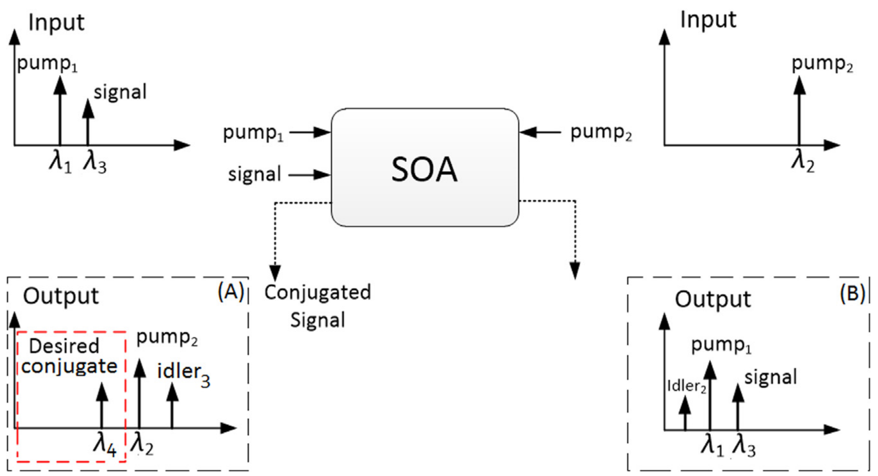

Fig. 1. Block-diagram of dual pumped counter-propagating FWM in SOA. Pumps are detuned from symmetrical position of signal to facilitate optical filtering of conjugate. λ_1 and λ_2: forward and backward pump wavelength, λ_3: signal, and λ_4: conjugate wavelength.