Photonic Frequency-Upconversion Efficiencies in Semiconductor Optical Amplifiers

Y.-K. Seo, J.-H. Seo, and W.-Y. Choi, *Member, IEEE*

***Abstract*—We investigated the characteristics of the photonic frequency-upconversion process in semiconductor optical amplifiers. We derived a simple analytical expression for the upconversion efficiency, and investigated its dependence on various parameters. We experimentally confirmed our results.**

***Index Terms*—Conversion efficiency, cross-gain modulation, radio-on-fiber systems, photonic frequency-upconversion, semiconductor optical amplifier (SOA).**

I. INTRODUCTION

THE RADIO-ON-FIBER technology has recently attracted much attention for broad-band radio access system applications [1]–[5]. For the increase of the total data traffic capacity, linking radio-on-fiber systems to the existing wavelength-division-multiplexing (WDM) networks is an important issue. For this, several schemes have been demonstrated using either Mach–Zehnder modulators (MZMs) [3], [4] or nonlinear photodetection of photodiodes (PDs) [5], where WDM data signals at different wavelengths are frequency-upconverted to the desired millimeter-wave frequencies. In addition, we have proposed and experimentally demonstrated an efficient photonic frequency-upconversion scheme using cross-gain modulation in a semiconductor optical amplifier (SOA) [6].

Fig. 1 shows the system configuration for our investigation. Unlike in [6] where an MZM is used for optical local oscillator (LO) signal generation, optical LO signals here are produced by the optical sideband injection locking technique employing three distributed feedback (DFB) lasers [7]. One laser, acting as master laser, is directly radio-frequency (RF) modulated by a subharmonic of the desired LO frequency, f_{LO}, and produces multiple sidebands. Two of these sidebands injection-lock two DFB lasers, acting as slave lasers, resulting in two optical modes separated by f_{LO}. The optical intermediate frequency (IF) signal is produced by the MZM intensity modulation at f_{IF}.

When optical IF and LO signals copropagate through an SOA and are detected by a PD, photonic frequency-upconversion of f_{IF} to lower sideband [(LSB) $f_{\mathrm{LO}} - f_{\mathrm{IF}}$] and upper sideband [(USB) $f_{\mathrm{LO}} + f_{\mathrm{IF}}$] is achieved with SOA cross-gain modulation and square-law photodetection. Two insets in Fig. 1 show photodetected RF spectra measured before and after SOA, where f_{LO} of 25 GHz and f_{IF} of 1 GHz are used. The postconversion LSB and USB signal powers are larger than the preconversion IF signal power indicating conversion gain.

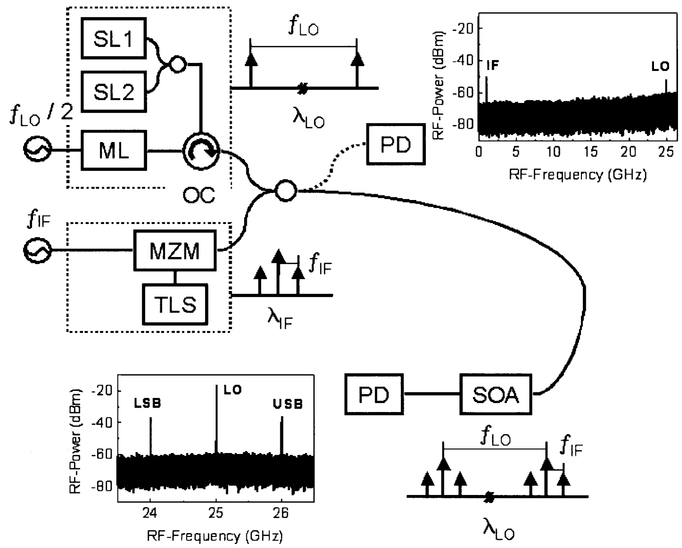

Fig. 1. Experimental setup for all-optical frequency-upconversion using SOA. TLS: tunable light source. ML: master laser. SL: slave laser. OC: optical circulator. In the experiment, $f_{\mathrm{IF}} = 1$ GHz and $f_{\mathrm{LO}} = 25$ GHz.

In this letter, the results of detailed investigation into the upconversion process in SOA are reported. Specifically, a simple analytical expression for the upconversion efficiency is derived and used for investigating how the conversion efficiency is influenced by various conditions such as SOA bias currents, LO intensities, input signal wavelengths, and IF modulation frequencies.

II. ANALYSIS AND EXPERIMENT

Our analysis is based on the approach given in [8]. When the fields of optical IF signal E_{IF} and optical LO signal E_{LO} enter the SOA at $z = 0$, their propagation in SOA and the change in SOA carrier density can be expressed as

$$\frac{dE_{\mathrm{IF,\,LO}}}{dz} = \frac{1}{2}\Gamma a_{\mathrm{IF,\,LO}}(N - N_{\mathrm{IF,\,LO}})E_{\mathrm{IF,\,LO}} \quad (1)$$

$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_S} - \sum_{i=\mathrm{IF,\,LO}} a_i(N - N_i)\frac{|E_i|^2}{\hbar\omega_i A_{\mathrm{eff}}} \quad (2)$$

where $a_{\mathrm{IF,\,LO}}$, $N_{\mathrm{IF,\,LO}}$, and $\omega_{\mathrm{IF,\,LO}}$ are the differential gain, the transparent carrier density, and the optical angular frequency for the optical IF and LO signals. Γ is the confinement factor, I the SOA injection current, q the electron charge, V the SOA active volume, τ_S the spontaneous carrier lifetime, $\hbar$ the plank

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The authors are with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: wchoi@yonsei.ac.kr).

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constant, and A_{eff} the effective mode area. Four-wave-mixing effects between the optical IF and LO signals in SOA are not taken into account for simplicity in analysis. The solution of (1) can be written as

$$E_{\mathrm{IF,\,LO}}(t,\,z) = E_{\mathrm{IF,\,LO}}(t,\,z=0) \cdot \exp\left\{\Gamma a_{\mathrm{IF,\,LO}}\left[\sigma(t,\,z) - N_{\mathrm{IF,\,LO}}z\right]/2\right\} \quad (3)$$

where, $\sigma(t,\,z) = \int_0^z N(t,\,z')\,dz'$ represents the spatially integrated carrier density. By integrating both sides of (2) with respect to z, we can obtain

$$\frac{d\sigma}{dt} = \frac{Iz}{qV} - \frac{\sigma}{\tau_S} - \sum_{i=\mathrm{IF,\,LO}} \frac{|E_i(t,0)|^2}{\Gamma\hbar\omega_i A_{\mathrm{eff}}} \cdot \left\{\exp\left[\Gamma a_i(\sigma - N_i z)\right] - 1\right\}. \quad (4)$$

When the optical IF signal is harmonically modulated and the optical LO signal has two optical modes separated by f_{LO} as described in Fig. 1, E_{IF} and E_{LO} can be written as

$$\begin{aligned} &E_{\mathrm{IF}}(t,\,z=0) \\ &= \sqrt{\overline{P}_{\mathrm{IF}}}\,\left(1 + m_{\mathrm{IM}}\cos\left(\Omega_{\mathrm{IF}}t\right)\right)^{1/2} \cdot e^{-j\omega_{\mathrm{IF}}t} \\ &= \left(\overline{P}_{\mathrm{IF}} + \Delta P_{\mathrm{IF}}e^{-j\Omega_{\mathrm{IF}}t} + \Delta P_{\mathrm{IF}}^{*}e^{j\Omega_{\mathrm{IF}}t}\right)^{1/2} \cdot e^{-j\omega_{\mathrm{IF}}t} \quad (5) \\ &E_{\mathrm{LO}}(t,\,z=0) \\ &= \sqrt{\overline{P}_{\mathrm{LO}}/2}\,\left(e^{-j\Omega_{\mathrm{LO}}t/2} + e^{j\Omega_{\mathrm{LO}}t/2}\right) \cdot e^{-j\omega_{\mathrm{LO}}t}. \quad (6) \end{aligned}$$

$\overline{P}_{\mathrm{IF,\,LO}}$ and $\Omega_{\mathrm{IF,\,LO}}$ $(=2\pi f_{\mathrm{IF,\,LO}})$ are the average light intensity and the angular electrical modulation frequency for the optical IF or LO signals. m_{IF} is the intensity modulation (IM) index and $\Delta P_{\mathrm{IF}} = \Delta P_{\mathrm{IF}}^{*} = (1/2)\,m_{\mathrm{IM}}\overline{P}_{\mathrm{IF}}$ for relatively small intensity modulation of the optical IF signal. If we assume that f_{LO} is much larger than the SOA gain modulation frequency bandwidth, which is the usual case in applications, then only optical IF signals have an influence on the SOA carrier density modulation with $\sigma = \sigma_S + \Delta\sigma e^{-j\Omega_{\mathrm{IF}}t} + \Delta\sigma^{*}e^{j\Omega_{\mathrm{IF}}t} \cdot \sigma_S$ is the spatially integrated steady-state carrier density and can be numerically obtained from the steady-state solution of (4), or $d\sigma/dt = 0$. From the first-order perturbation of (4), we can obtain

$$\Delta\sigma = -\frac{(G_{\mathrm{IF}} - 1)\,\Delta P_{\mathrm{IF}}}{\Gamma\hbar\omega_{\mathrm{IF}}A_{\mathrm{eff}}\left(-j\Omega_{\mathrm{IF}} + \gamma_{\mathrm{eff}}\right)}$$

and

$$\Delta\sigma^{*} = -\frac{(G_{\mathrm{IF}} - 1)\,\Delta P_{\mathrm{IF}}^{*}}{\Gamma\hbar\omega_{\mathrm{IF}}A_{\mathrm{eff}}\left(j\Omega_{\mathrm{IF}} + \gamma_{\mathrm{eff}}\right)} \quad (7)$$

where

$$\gamma_{\mathrm{eff}} = 1/\tau_S + 1/\tau_{S_{\mathrm{IF}}} + 1/\tau_{S_{\mathrm{LO}}}$$

and

$$\tau_{S_{\mathrm{IF,\,LO}}} = \tau_S A_{\mathrm{eff}}\hbar\omega_{\mathrm{IF,\,LO}}/G_{\mathrm{IF,\,LO}}a_{\mathrm{IF,\,LO}}\overline{P}_{\mathrm{IF,\,LO}}.$$

In the above equations, γ_{eff} is the effective recombination rate, $G_{\mathrm{IF,\,LO}} = \exp[\Gamma a_{\mathrm{IF,\,LO}} \cdot (\sigma_S - N_{\mathrm{IF,\,LO}}z)]$ the optical gain, and $\tau_{S_{\mathrm{IF,\,LO}}}$ the stimulated recombination lifetime for the optical IF or LO signals. Using (7) together with (6), the optical LO signal after SOA can be written as

$$\begin{aligned} \tilde{E}_{\mathrm{LO}}(t) = &\sqrt{\frac{G_{\mathrm{LO}}\overline{P}_{\mathrm{LO}}}{2}}\,\left(e^{-j\,(1/2)\,\Omega_{\mathrm{LO}}t} + e^{j\,(1/2)\,\Omega_{\mathrm{LO}}t}\right) \\ &\cdot e^{-j\omega_{\mathrm{LO}}t}\left(1 + \tfrac{1}{2}\,\Gamma a_{\mathrm{LO}}\,\Delta\sigma e^{-j\Omega_{\mathrm{IF}}t}\right. \\ &\left. + \tfrac{1}{2}\,\Gamma a_{\mathrm{LO}}\,\Delta\sigma^{*}e^{j\Omega_{\mathrm{IF}}t}\right) \end{aligned} \quad (8)$$

with the approximation of $e^x \approx 1 + x$. Equation (8) shows that the SOA carrier density modulation by the optical IF signal produces new sidebands at $\omega_{\mathrm{LO}} \pm ((1/2)\,\Omega_{\mathrm{LO}} \pm \Omega_{\mathrm{IF}})$ in the spectrum of optical LO signals. They are the results of the SOA cross-gain modulation, because optical IF signals modulate the SOA carrier density, which in turn modulates optical LO signals at $\omega_{\mathrm{LO}} \pm (1/2)\,\Omega_{\mathrm{LO}}$. The photodetected current after SOA can be obtained from $\tilde{I}_{\mathrm{LO}}^{\mathrm{PD}}(t) = R_{\mathrm{PD}}|\tilde{E}_{\mathrm{LO}}(t)|^2$ and its USB signal current at $f = f_{\mathrm{LO}} + f_{\mathrm{IF}}$ is given as $\tilde{I}_{\mathrm{LO}}^{\mathrm{PD}}(f_{\mathrm{LO}} + f_{\mathrm{IF}}) = R_{\mathrm{PD}}G_{\mathrm{LO}}\overline{P}_{\mathrm{LO}}\Gamma a_{\mathrm{LO}}\,\Delta\sigma^{*}/2$, where R_{PD} is the PD responsivity. The photodetected IF signal current before SOA can be written as $I_{\mathrm{IF}}^{\mathrm{PD}}(f_{\mathrm{IF}}) = R_{\mathrm{PD}}\,\Delta P_{\mathrm{IF}}$ from (5). Then, the frequency-upconversion efficiency in the RF spectrum can be derived as

$$\eta_C = \left|\frac{\tilde{I}_{\mathrm{LO}}^{\mathrm{PD}}\left(f_{\mathrm{LO}} + f_{\mathrm{IF}}\right)}{I_{\mathrm{IF}}^{\mathrm{PD}}\left(f_{\mathrm{IF}}\right)}\right|^2 = \left|\frac{G_{\mathrm{LO}}a_{\mathrm{LO}}\overline{P}_{\mathrm{LO}}\left(G_{\mathrm{IF}} - 1\right)}{2\hbar\omega_0 A_{\mathrm{eff}}\left(j\Omega_{\mathrm{IF}} + \gamma_{\mathrm{eff}}\right)}\right|^2. \quad (9)$$

Equation (9) shows that the conversion efficiency is proportional to SOA optical gain and LO light intensity. Fig. 2(a) shows the calculated results for the frequency-upconversion efficiency at various bias conditions and LO intensities. For calculations, SOA parameters given in [9] are used. The coupling loss of 7 dB is assumed for SOA [10]. The conversion efficiency increases initially with LO intensity, but if LO intensity is too large, the conversion efficiency begins to decrease. This is because of the SOA optical gain saturation. The experimental validation is given in Fig. 2(b) where a commercially available SOA (Samsung OA40B3A) is used. Since we do not know the numerical values of the parameters for the SOA used in the experiment, we can only make a qualitative comparison at present.

The conversion efficiency can also vary depending on the optical IF and LO signal wavelengths simply because the optical gain in an SOA is wavelength-dependent. Fig. 3 shows

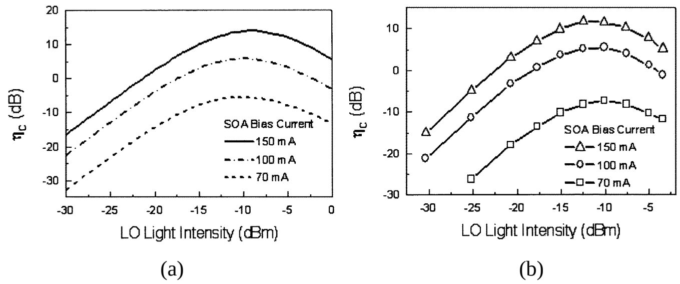

Fig. 2. (a) Calculated and (b) experimental results of signal-frequency-upconversion efficiency with LO light intensity for $\overline{P}_{\mathrm{IF}} = -10$ dBm, $f_{\mathrm{IF}} = 1$ GHz, $f_{\mathrm{LO}} = 25$ GHz, $\lambda_{\mathrm{IF}} = 1540$ nm, and $\lambda_{\mathrm{LO}} = 1552$ nm.

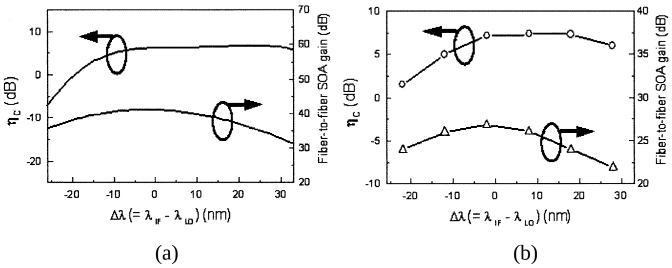

Fig. 3. Frequency-upconversion efficiency for different SOA input wavelengths when SOA is biased at 100 mA, $\overline{P}_{\rm IF} = -10$ dBm, $\overline{P}_{\rm LO} = -11$ dBm, $f_{\rm IF} = 1$ GHz, and $f_{\rm LO} = 25$ GHz. $\lambda_{\rm IF}$ is wavelength-tuned off from $\lambda_{\rm LO}$ of (a) 1540 nm in calculation and (b) 1552 nm in measurement.

the calculated and measured frequency-upconversion efficiencies for different IF wavelengths with optical LO wavelength fixed near the SOA gain peak. For comparison, the fiber-to-fiber SOA gain for the SOA light input power of −40 dBm is also shown. As can be predicted by (9), high upconversion efficiencies can be achieved as long as the SOA input wavelengths are within the SOA optical gain bandwidth. In particular, as the optical IF wavelength gets close to the optical gain peak, higher efficiency is achieved. In Fig. 3, the maximum conversion efficiency is achieved at the wavelength slightly longer than the gain peak wavelength for −40-dBm input power. It is because the decreased SOA carrier density by the optical IF and LO signals shifts the optical gain peak toward the longer wavelength.

Equation (9) shows that the effective recombination rate, $\gamma_{\rm eff}$, limits the SOA conversion efficiency and thus, the conversion efficiency has an optical IF frequency limit [8]. From (9), the 3-dB modulation frequency for the conversion efficiency can be derived as

$$f_{\rm IF}^{3\text{-dB}} = \frac{1}{2\pi}\gamma_{\rm eff} = \frac{1}{2\pi}\left(\frac{1}{\tau_S} + \sum_{k={\rm IF,\,LO}} \frac{a_k G_k \overline{P}_k}{\tau_S A_{\rm eff}\hbar\omega_k}\right). \tag{10}$$

As an example, Fig. 4 shows the calculated frequency modulation responses of the conversion efficiency at several SOA bias currents. $f_{\rm IF}^{3\text{-dB}}$ increases with SOA bias currents because it is proportional to the optical gain provided by SOA. It should be noted that this IF frequency limit for the optical IF signal does not pose any problem in applications, because the typical radio-on-fiber systems have IF frequencies not exceeding the gigahertz range.

III. Conclusion

We have investigated detailed characteristics for the frequency-upconversion of optical IF signals with the optical heterodyne LO signals having different wavelengths that can be achieved with SOA cross-gain modulation and square-law photodetection. For the better understanding of the signal-frequency-upconversion process, we have derived a simple analytical expression for the frequency-upconversion efficiency and provided experimental validation. Our results show that the signal-frequency-upconversion efficiency is directly attributed by the SOA optical gain and can be optimized by either controlling the optical LO power or selecting the optical IF and LO wavelengths within the SOA optical gain bandwidth. These results will be useful in selecting proper conditions for the optimal frequency-upconversion efficiency.

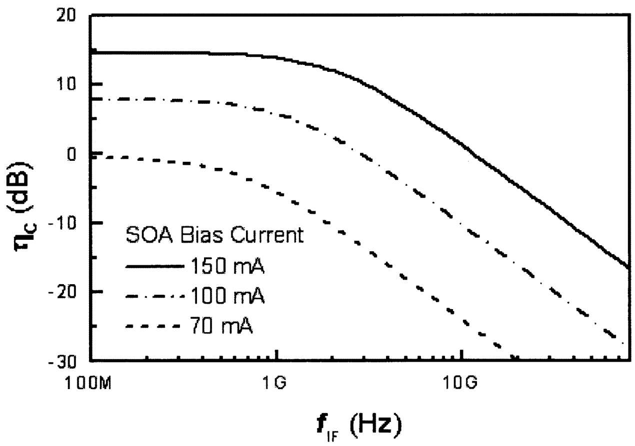

Fig. 4. Calculated frequency responses of the frequency-upconversion efficiency for different SOA bias currents when $\lambda_{\rm LO} = 1552$ nm, $\lambda_{\rm IF} = 1540$ nm, and $\overline{P}_{\rm IF} = \overline{P}_{\rm LO} = -10$ dBm.

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