All-Optical Signal Up-Conversion for Radio-on-Fiber Applications Using Cross-Gain Modulation in Semiconductor Optical Amplifiers

Y.-K. Seo, C.-S. Choi, and W.-Y. Choi

***Abstract*—The authors present a novel scheme of up-converting optical intermediate frequency (IF) signals with an optical local oscillator (LO) signal using cross-gain modulation in a semiconductor optical amplifier. This scheme provides high conversion efficiency and is independent of the incident light wavelength and polarization. It can be useful for radio-on-fiber transmission system applications in which one remote LO signal is provided for several wavelength-division-multiplexing IF signals.**

***Index Terms*—All-optical signal up-conversion, cross-gain modulation, radio-on-fiber application, semiconductor optical amplifier, signal conversion efficiency.**

I. Introduction

THE FIBER-OPTIC transmission of radio signals has attracted much attention for broad-band radio access system applications because it can simplify base station configuration [1]–[5]. For the increase of the total data traffic capacity, the wavelength-division-multiplexing (WDM) technique can be introduced to the radio-on-fiber systems. Millimeter-wave-over-fiber distribution schemes have been demonstrated, in which WDM data signals having different wavelengths were up-converted to the millimeter-wave frequency using Mach–Zehnder modulator (MZM) [1],[2] However, signal up-conversion using MZM has several problems. Its modulation characteristics depend on the incident wavelength and polarization, and it has a significant amount of insertion loss. In addition, the MZM modulation bandwidth can impose a limitation on the accessible frequency ranges for up-conversion. The technique of optoelectronic mixing has been demonstrated. Photodetected intermediate frequency (IF) data signals at the base station were mixed with the electric local oscillator (LO) signals by utilizing nonlinearity in three terminal devices such as high-electron mobility transistors (HEMTs) [3] and heterojunction bipolar transistor (HBTs) [4]. These methods, however, require high frequency electrical LO signal sources at base stations, which will increase the design complexities of base stations. In order to avoid these limitations, an all-optical approach has been tried, where optical IF and optical LO signals having different wavelengths can be utilized. In [5], IF signal up-conversion to the millimeter-wave frequency was realized by taking advantage of the nonlinear photodetection behavior of a high-speed photodetector (PD). This signal up-conversion scheme, however, has low conversion efficiency.

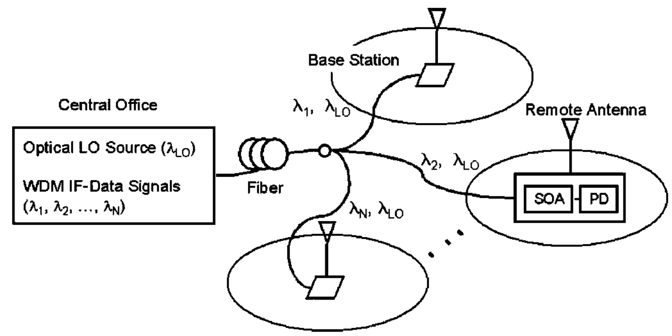

Fig. 1. Radio-on-fiber system configuration for WDM IF signals sharing one optical LO signal.

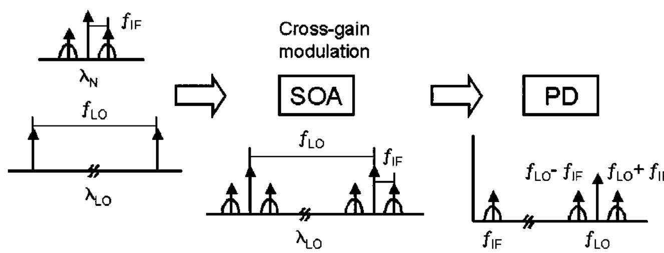

Fig. 2. All-optical signal up-conversion using XGM in SOA.

This letter deals with a new all-optical signal up-conversion scheme using a semiconductor optical amplifier (SOA). The radio-on-fiber system configuration that we have in mind is shown in Fig. 1, where one optical LO signal is distributed to several base stations and IF signals are wavelength selectively transmitted to base stations. The optical LO signal has two optical sidebands separated by the desired LO frequency (f_{LO}) and is shared among base stations. All-optical conversion of the IF signal (f_{IF}) to lower sideband (LSB, $f_{\mathrm{LO}} - f_{\mathrm{IF}}$) and upper sideband (USB, $f_{\mathrm{LO}} + f_{\mathrm{IF}}$) is achieved in combination with the SOA cross-gain modulation (XGM) and square-law photodetection as described in Fig. 2.

The mixing of two RF-modulated optical signals in SOA has been demonstrated [6]. In this case, however, the RF modulation of both optical signals was limited within the SOA gain modulation bandwidth. In this letter, it is demonstrated that such a limitation is not necessary for both optical LO and IF signals. If only one of them (in our case, optical IF signal fre-

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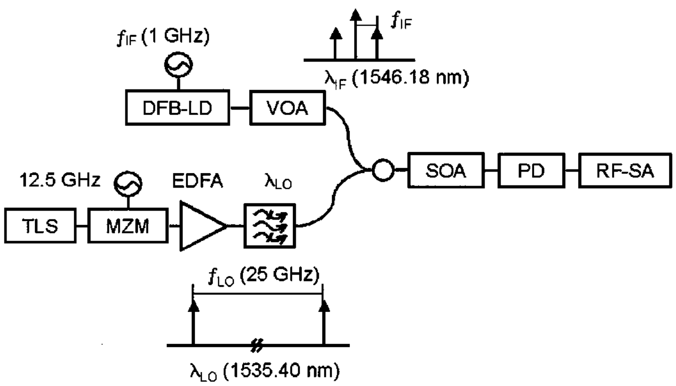

Fig. 3. Experimental setup for all-optical signal up-conversion using SOA. TLS, VOA, and RF-SA represent tunable light source, variable optical attenuator, and RF-spectrum analyzer, respectively.

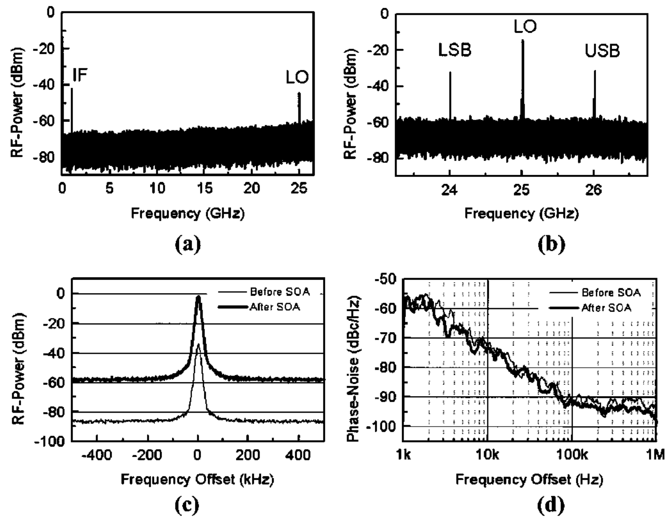

Fig. 4. Measured RF-spectra and phase noises before and after SOA, when SOA is biased at 150 mA. (a) and (b) are RF-spectra for pre-and postup-conversion. (c) Both at finer scale. (d) Single-sideband phase noises of 25-GHz LO signals before and after SOA.

quency) is within the SOA gain modulation bandwidth, successful up-conversion is possible. Using this, optical LO frequency much higher than the SOA gain modulation bandwidth can be utilized, which is quite useful for radio-on-fiber applications. In addition, our scheme does not have wavelength or polarization dependence, and signal up-conversion is possible for a wide range of separation between IF and LO wavelengths as long as both are within the range of SOA optical gain.

II. Experiment and Results

Fig. 3 shows the experimental setup used for demonstrating all-optical signal up-conversion with an SOA. Optical LO signals are generated from an MZM biased at V_π for double sideband-suppressed optical carrier (DSB-SC) modulation [2] in order to obtain two optical sidebands separated by the LO frequency. The LO frequency of 25 GHz is chosen because of the limited modulation bandwidth of the MZM available in the experiment, but the present scheme should be applicable for much higher LO frequencies. The MZM output is amplified by erbium-doped fiber amplifiers (EDFA) in order to compensate the loss from the MZM DSB-SC modulation and spectrally filtered out by an optical bandpass filter to eliminate EDFA-induced noises. Additional gain provided by EDFA would not be needed if optical LO signals with higher optical power are available as in the case of optical heterodyne techniques [7].

The optical IF signal is produced by the direct modulation of a DFB-LD at 1 GHz. The optical IF peak power is set at -10.9 dBm with an optical attenuator at the SOA input port. For simplicity, no modulated data are added to IF. Optical IF and LO signals copropagate through SOA. The LO signal wavelength ($\lambda_{\mathrm{LO}} = 1535.40$ nm) was separated from the IF signal wavelength ($\lambda_{\mathrm{IF}} = 1546.18$ nm) by about 11 nm. The SOA (Samsung OA40B3A) used in the experiment has less than 1-dB polarization dependence loss and has, when biased at 150 mA, larger than 40 nm of optical gain wavelength range, larger than 5 dBm in output saturation power, and about 3 GHz of gain modulation bandwidth. No polarization control is used. An optical attenuator is placed before the photodiode (PD) in order to avoid any nonlinear photodetection at the large optical power [5], which may interfere with the up-conversion process.

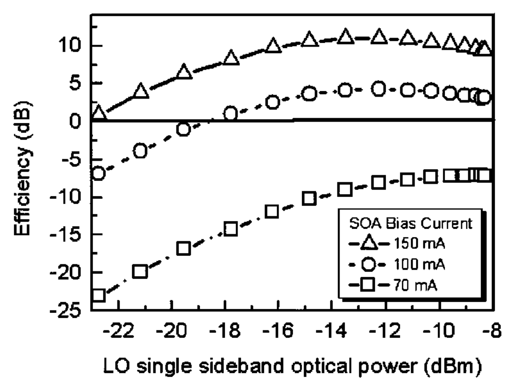

Fig. 5. Up-conversion efficiency with varying optical LO power at several SOA bias currents.

Fig. 4(a) and (b) shows the RF-spectra of IF and LO signals measured before and after SOA. One can observe clearly that, after optical IF and LO signals copropagate through the SOA, the IF signal at 1 GHz is up-converted to LSB (24 GHz) and USB (26 GHz). In addition, these LSB and USB signals [see Fig. 4(b)] have larger RF powers by about 10 dB compared to IF signal power before SOA [see Fig. 4(a)]. This implies that the SOA provides gain to the up-conversion process. With this, the conversion efficiency is much larger than in schemes using external optical modulators [2] or high speed PDs [5]. Although amplified spontaneous emission in SOA enhances the overall noise level [see Fig. 4(c)], the phase–noise degradation of the LO signal is negligible as shown in the single-sideband phase–noise measurement results shown in Fig. 4(d).

In order to investigate the dependence of conversion efficiency, the up-converted USB RF-powers are measured as functions of various SOA bias currents and optical LO powers for one fixed optical IF power (-10.9 dBm). The results are shown in Fig. 5. The conversion efficiency is defined as the ratio of the up-converted USB RF-power to the IF RF-power, measured from the photodetected currents with and without SOA, respectively. Fig. 5 shows that the up-conversion efficiency increases with SOA bias current levels indicating that the conversion efficiency is directly attributed by the optical gain in SOA. Fig. 5 also shows that the efficiency initially increases with the LO power but decreases after a certain level. This is due to the SOA gain saturation. We have also confirmed experimentally that up-conversion is possible even when optical LO and IF signals have the identical wavelength, and as long as both optical LO and IF wavelengths are within the SOA optical gain range, which is about 40 nm in the present case. In addition, up-conversion is possible for the wide range of IF frequencies as long as they are within the SOA gain modulation bandwidth.

III. Conclusion

We presented a new all-optical signal up-conversion scheme using an XGM effect in SOA. Specifically, we demonstrated experimentally that all-optical signal up-conversion is possible for the LO frequency that is much larger than SOA modulation frequency and with positive conversion efficiency. In addition, the wavelengths of optical LO and IF wavelength can have a wide separation. These features are very useful for radio-on-fiber transmission system applications in which one remote optical LO signal is provided for several WDM IF (or baseband) signals at different wavelengths.

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