Spurious-Free Dynamic Range Characteristics of the Photonic Up-Converter Based on a Semiconductor Optical Amplifier

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***Abstract*—We investigate nonlinear intermodulation distortion characteristics of the photonic up-converter based on a semiconductor optical amplifier for multifrequency signal up-conversion. The third-order intermodulation distortions are measured with two-tone intermediate frequency signals for the photonic up-converter under various conditions. The spurious-free dynamic range is determined to be larger than 72 dB $\cdot$ Hz$^{2/3}$.**

***Index Terms*—Cross-gain modulation (XPM), intermodulation distortion, photonic frequency up-conversion, semiconductor optical amplifiers (SOAs), spurious-free dynamic range (SFDR), subcarrier multiplexing.**

I. INTRODUCTION

RADIO-ON-FIBER (RoF) systems are attracting much attention for broad-band wireless applications such as wireless local area networks and intelligent traffic systems [1]–[6]. As the service data rate increases, higher carrier frequencies up to millimeter wave (MMW) range are needed. The remote up-conversion scheme is one promising candidate to realize MMW RoF systems, in which baseband or intermediate frequency (IF) signals are optically transmitted from the central station to base stations, and up-converted to desired MMW frequencies at base stations [2]. To realize such base stations, MMW-range electrical mixers and local oscillators (LOs) are required, which make base stations complex and expensive. In order to overcome these problems, photonic up-conversion techniques have been proposed, which utilize optically generated LO signals and optical components such as nonlinear photodiodes (PDs) [3], electroabsorption modulator–transceiver [4], and Mach–Zehnder modulators (MZMs) [5], [6]. We also proposed a photonic up-conversion method using cross-gain modulation (XGM) of the semiconductor optical amplifier (SOA). Fig. 1 schematically shows the up-conversion process. The SOA photonic up-converter has high conversion efficiency, unlimited LO frequency as long as a high-speed PD is available, and wide wavelength range [7], [8].

The subcarrier multiplexing method is very useful for RoF systems since it can merge several applications together [3], [6] and provide frequency sectorization schemes [9], which are important for many wireless applications. Therefore, the data buried in multiple IF frequencies should be up-converted simultaneously when photonic up-converters are used. However, since any frequency up-converter is based on nonlinear properties of the device used, intermodulation distortion products from multichannel up-conversion are inevitable. These distortion products can degrade system performance severely. Consequently, investigation into distortion characteristics of our SOA-based photonic up-converter is necessary.

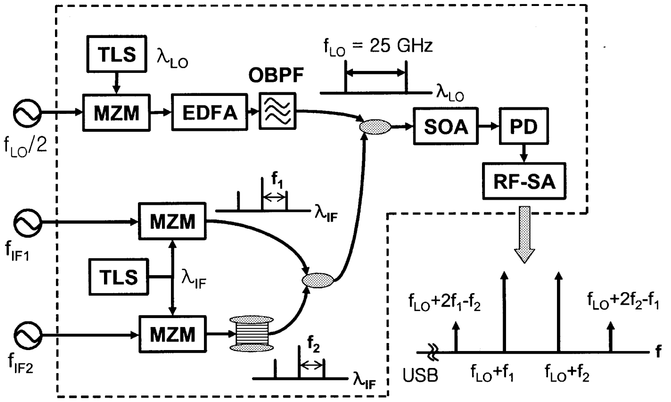

Fig. 1. Experimental setup for the SFDR measurement for the third-order distortion. TLS: tunable laser source. OBPS: optical bandpass filter. RF-SA: RF spectrum analyzer.

In this letter, we investigate nonlinear intermodulation distortion properties of the SOA-based photonic up-converter under various conditions such as different optical LO input powers and IF signal wavelengths. The third-order intermodulation distortions are measured for the case of two-tone IF signals, and the resulting spurious-free dynamic range (SFDR) is determined.

II. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental setup used for our investigation. The optical heterodyne LO signals at $\lambda_1 = 1555$ nm, having two modes separated by f_{LO} of 25 GHz, were generated by the double sideband suppressed carrier modulation method [5], for which MZM biased at V_π was modulated by 12.5-GHz radio-frequency (RF) signal. Because the resulting LO power was very small, an erbium-doped fiber amplifier was used, and its amplified spontaneous emission (ASE) effects were reduced by an optical bandpass filter having 0.4-nm bandwidth. For generating IF subcarriers, two MZMs biased at the quadrature point were intensity-modulated independently at 995 (f_1) and 1005 MHz (f_2). The reason for using two modulators

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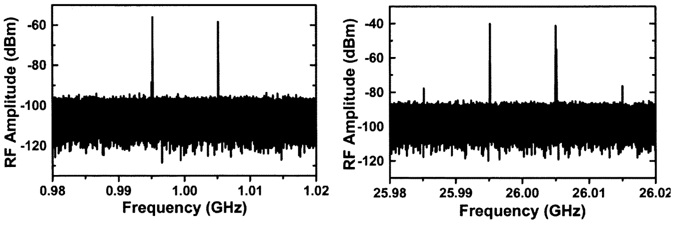
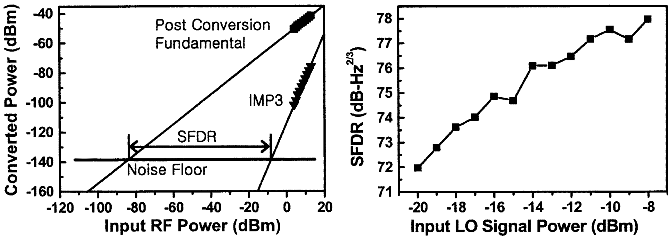


(a) (b)

Fig. 2. (a) RF spectra for the IF signals before SOA and (b) up-converted USB RF signals. Each LO signal power is −13 dBm at 1555 nm and total IF signal power is −13 dBm at 1545 nm. The resolution bandwidth of two spectra is 3 kHz.



(a) (b)

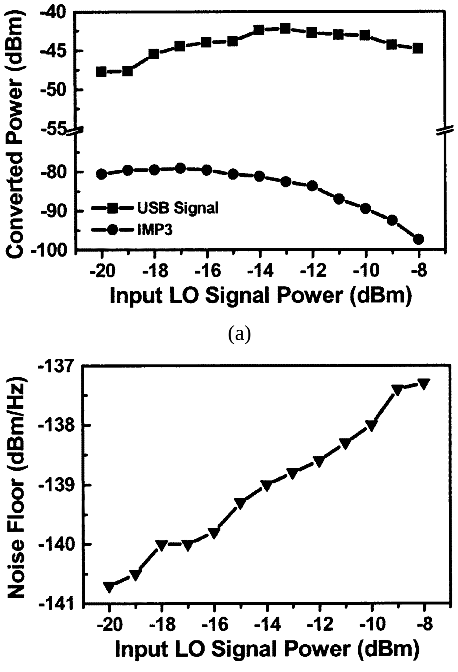
Fig. 3. (a) SFDR measurement example for −14-dBm LO signal power and (b) the dependence of the photonic up-converter SFDR on optical LO signal power.

is to prevent the influence of the third-order intermodulation distortion effects of the modulator itself. We utilized only one tunable optical source for two modulators to avoid complexities from the unwanted four-wave mixing terms produced by two optical sources with closely spaced wavelengths. In addition, by using one IF wavelength, we could unambiguously determine dependence of up-converter SFDR on IF wavelength.

In order to prevent coherent beating between two optical IF signals that makes detected signals unstable, an optical delay line was introduced at one modulator output path. The optical powers for IF signals were controlled with variable optical attenuators so that detected RF powers were equal. Optical sources used in the experiment were tunable external cavity lasers, which did not act as the dominant noise source. As a receiver, we used an Agilent lightwave converter having 24-dB RF gain and 30 pW/Hz$^{1/2}$ noise equivalent power at the 25-GHz band. In order to eliminate influence of PD nonlinearity [3], a 10-dB optical attenuator is used before PD, which reduced the received RF power as well as the detected noise floor. The SOA used in the experiment has less than 1-dB polarization-dependent gain. Consequently, no active control of polarization is required for the SOA up-converter.

Fig. 2 shows measured RF spectra for IF and up-converted upper sideband (USB) signals before and after photonic up-conversion, respectively. When optical LO signals and IF signals copropagate through the SOA, optical LO signals experience XGM produced by two IF subcarriers, and after photodetection, IF subcarriers are up-converted [7]. The up-converted USB signals at 25.995 $(f_{\rm LO} + f_1)$ and 26.005 GHz $(f_{\rm LO} + f_2)$ and the third-order intermodulation distortion products (IMP3 s) at the frequencies of 25.985 $(f_{\rm LO} + 2f_1 - f_2)$ and 26.015 GHz $(f_{\rm LO} + 2f_2 - f_1)$ are clearly observed in Fig. 2(b).

For SFDR measurement, we observed powers of the 26.005-GHz $(f_{\rm LO} + f_2)$ USB signal and the IMP3 at 26.015 GHz $(f_{\rm LO} + 2f_2 - f_1)$. Fig. 3(a) shows an example of SFDR measurement results. For this measurement, the SOA input optical LO signal power was set at −14 dBm and the total SOA input optical power for IF signals at 1545 nm was −13 dBm. Since the RF-spectrum analyzer (HP 8563E) used in our investigation has noise display limit of about −130 dBm/Hz at the 25-GHz band, we intentionally enhanced the noise floor by an electrical amplifier having 17-dB RF gain and 4-dB noise figure for noise floor level measurement. It was made sure that the distortion of the amplifier was low enough not to affect our SFDR measurement. Then, the noise-floor level was determined by subtracting amplifier gain from the enhanced noise floor due to the additional amplifier. The measured noise floor for the case shown in Fig. 3(a) was −139 dBm/Hz. The excess noise of the added electrical amplifier itself could be ignored because the dominant noise source was the lightwave converter. For the noise-floor measurement, the RF modulation power for IF signals was set at −20 dBm. The SFDR was determined to be 76.1 dB · Hz$^{2/3}$, as can be seen in Fig. 3(a).



(a)

(b)

Fig. 4. Converted USB signal and IMP3 powers according to SOA input LO signal power for (a) RF modulation power of 12 dBm and (b) measured noise floors after the lightwave converter.

We measured the SFDR as a function of SOA input optical LO signal powers ranging from −20 to −8 dBm with 1-dB increment. The optical IF signals had in total −13-dBm SOA input power at 1545-nm wavelength. The SOA was biased at 150 mA. Fig. 3(b) shows the SFDR measurement results. As the LO signal power increases, the SFDR increases continuously from about 72 to 78 dB · Hz$^{2/3}$. In order to understand this increase, we show in Fig. 4 the up-converted USB signal power and IMP3 power at 12-dBm input RF power condition as well as the noise-floor level. With 12-dBm input RF power, the detected USB and IMP3 power are not saturated. The dependence of USB signal on LO signal power follows the up-conversion

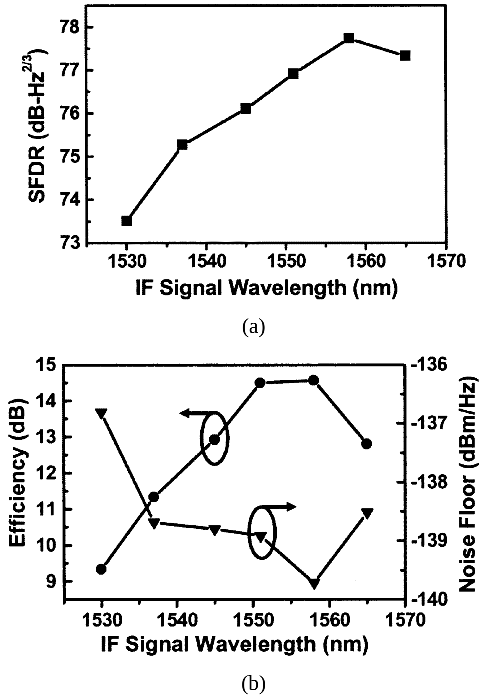


Fig. 5. (a) Dependence of the photonic up-converter SFDR on optical IF signal wavelength and (b) up-conversion efficiencies and noise-floor characteristics as a function of the IF signal wavelengths.

efficiency defined as the RF power ratio between preconversion IF signal and post-conversion USB signal [7], [8]. When the LO signal power is low, the post-conversion USB signal power increases continuously. Compared with this, the increase of the IMP3 power and noise floor is insignificant. Consequently, the SFDR increases. When the LO signal power is high, the USB signal power is saturated due to the SOA gain saturation [7], [8] and the noise-floor level rises continuously [10]. The SFDR increases, however, because distortion product powers get reduced very much as the LO signal power increases. For example, when the LO signal power increased from -13 to -8 dBm, the USB signal power and noise floor changed about 1–2 dB, but the distortion product power decreased by 15 dB. We believe that this low distortion at high LO power is the result of heavily depleted carriers in SOA caused by high SOA input power.

Finally, we measured the SFDR dependence on the input IF signal wavelength. The total SOA input IF signal power was again fixed at -13 dBm, and the IF wavelength was changed within the C-band (1530–1565 nm), which covers the gain bandwidth of SOA biased at 150 mA. The LO signal power was fixed at -13 dBm. Fig. 5(a) shows the measured SFDR as a function of the IF signal wavelengths. Within the C-band, the SFDR changes from about 73 to 77 dB $\cdot$ Hz$^{2/3}$. In this case, the SFDR characteristics are determined by the up-conversion efficiency and the noise-floor level. As explained in [7] and [8], the up-conversion efficiency is determined by the SOA gain spectrum, and the efficiency is highest at the SOA gain peak wavelength. However, the noise-floor change is inversely proportional to the SOA gain spectrum at the saturated SOA so that it has the minimum at the gain peak wavelength [11]. Fig. 5(b) shows these characteristics very well. Therefore, the dependence of the SFDR on IF wavelength also follows the SOA gain spectrum, and the maximum SFDR is obtained when IF signal wavelength is at the SOA gain peak.

The SFDR of our photonic up-converter is not high compared with that of the conventional 30-GHz band electrical mixers. Some important reasons are PD output power saturation and ASE of SOA. We believe that the SFDR can be improved by using a PD with high output saturation power with which the unwanted optical attenuation in front of PD can be eliminated, and an optical filter after SOA with which ASE can be reduced.

III. CONCLUSION

We have investigated the nonlinear characteristics of the photonic SOA up-converter using SFDR measurement under various conditions such as optical LO signal powers and IF signal wavelengths. It is found that the SFDR increases with the LO signal power despite the up-conversion efficiency saturation and noise-floor increase. We also investigated the dependence of the SFDR on IF signal wavelengths, which follows the SOA gain spectrum. The SFDR larger than 72 dB $\cdot$ Hz$^{2/3}$ was obtained in our investigation.

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