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Optoelectronic RF Signal Mixing Using an Electroabsorption Waveguide as an Integrated Photodetector/Mixer

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Abstract—We demonstrate for the first time an electroabsorption (EA) waveguide utilized as an integrated photodetector/mixer for frequency conversion of radio frequency signals, through field-controlled absorption. Using an InAsP–GaInP multiple-quantum-well EA waveguide, a conversion loss of 18.9 dB was obtained at 10-mW optical local oscillator (LO) power, and a suboctave, two-tone spur-free dynamic range of 120.0 dB-Hz^{4/5} was measured for an up-converted signal at 1.9 GHz. This scheme can be useful in antenna applications where optical LO signal distribution is used for frequency converting microwave signals.

Index Terms—Electroabsorption, frequency conversion, optoelectronic mixer, radio-frequency signal mixing, spur-free dynamic range.

I. INTRODUCTION

RADIO-FREQUENCY (RF) photonics technology is now considered a very viable alternative in application areas where electronics has traditionally played the central role. Wide-bandwidth, lightweight, high degree of security, long-distance remoting capability, and immunity to electromagnetic interference are some of the advantages to be gained. Recently, sending down-converted RF signals over the fiber has received much attention, as it avoids costly high-speed photodetectors and fiber dispersion at high RF frequency [1], [2]. Many of the conversion schemes take advantages of the optical local oscillator (LO), which is simpler than the electronic LO at high frequency, and has less phase noise [3]. There have been several attempts to achieve low conversion loss and large spur-free dynamic range (SFDR) for frequency-converted photonic links [4]–[6]. In [5], monolithic series Mach–Zehnder modulators were used with very high optical LO power (350 mW) to achieve link conversion gain (defined as the ratio

of the output converted RF power to the input RF power) of 17 dB and 3.3 dB, with and without impedance matching, respectively. Using this approach, a SFDR of 112.9 dB-Hz^{2/3} was achieved. The SFDR was increased to 122.5 dB-Hz^{4/5}, using a linearized LiNbO₃ modulator with 364-mW optical LO power [6]. Another recent approach used either a heterojunction phototransistor or heterojunction bipolar transistor (HBT) to convert the optically modulated RF signal by utilizing the inherent nonlinearity of the device [7]–[9]. In [8], a 10.4-dB intrinsic conversion gain was achieved using an electrical LO. Using an HBT with low external quantum efficiency, however, the external conversion gain was –5.5 dB with a three-stub tuner. In [9], two HBT's in a cascode configuration were used to achieve an intrinsic conversion gain of 18.2 dB and an extrinsic conversion gain of 7.4 dB with a three-stub tuner. To date, no RF link SFDR measurement has been reported using the HBT as an optoelectronic mixer (OEM).

In this letter, a different scheme of RF signal conversion is proposed using an EA waveguide as an integrated photodetector/mixer. Unlike previous approaches [1], [2], [4]–[6], frequency converted *electrical* RF signals from an EA waveguide, operating as an OEM, are generated and made available for subsequent signal processing. The down-converted RF signal can be sent through conventional electrical cable that has low attenuation at low frequency, or processed locally near the antenna using usually inexpensive electronics. This approach avoids using high optical LO power to compensate the fiber link RF loss, while still taking advantage of distributing optical LO in the proximity of the antenna elements. In this letter, moderate conversion loss and high SFDR RF signal mixing is demonstrated with moderate optical LO power and a simple system configuration.

II. THEORY

As optical power is incident on an EA waveguide, the electroabsorption (EA) generates an electric-field-dependent photocurrent I_{ph} expressed as $I_{ph}(V, P_{opt}) = \eta_m(V)P_{opt}$, where P_{opt} is the optical power and $\eta_m(V)$ is the EA waveguide's detection responsivity. As depicted in Fig. 1, η_m is dependent on the applied bias (therefore, the electric field), and is independent of optical power provided the device is operated below saturation. For an optical signal with RF modulation at ω_{LO} incident on an EA waveguide driven with a dc bias voltage V_b , along with

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a RF signal voltage v at ω_s , up-and down-converted signals at $\omega_s \pm \omega_{LO}$ are obtained as

$$I_{ph}^{mix} = \frac{1}{2} \frac{d\eta_m}{dV} \Big|_{Vb} vp \cos(\omega_s \pm \omega_{LO})t \quad (1)$$

where

$(d\eta_m/dV)|_{Vb}$ first-order derivative evaluated at the dc bias voltage;

p modulation optical power at ω_{LO} .

The higher-order derivatives of η_m will contribute to the harmonic and intermodulation distortions of this OEM. Note from $(d\eta_m/dV)|_{Vb}$ in (1) that the field-controlled absorption is crucial in generating mixed signals. This distinguishes the EA waveguides in the detector mode [10] from the usual pin photodetector that is biased to give a constant responsivity with voltage.

III. EXPERIMENTS AND DISCUSSION

In the experiments, an anti-reflection coated strain-compensated InAsP-GaInP multiple-quantum-well (MQW) EA waveguide that utilizes the quantum-confined Stark effect (QCSE) was used [11]. The undoped electroabsorption layer was composed of 8 periods of 8.9-nm-thick compressively-strained InAsP wells and 7.4-nm-thick tensile-strained GaInP barriers, sandwiched by InGaAsP cladding layers. At an optical power of 10 mW ($\lambda = 1.319 \mu\text{m}$), the transmission (as detected by a remote detector with 0.89-A/W responsivity) and device photocurrent characteristics versus dc bias of this EA waveguide are shown in Fig. 1 for TE polarization. The fiber-to-fiber insertion loss of this waveguide as a modulator was estimated to be 8.0 dB. The electrical 3-dB bandwidth of this device was separately measured to be 4.8 GHz without impedance matching. The length of this waveguide device was $185 \mu\text{m}$.

The RF frequency mixing experiment was set up as shown in Fig. 2. Two Nd:YAG lasers were set up to generate a beat frequency at 900 MHz with 100% modulation depth, which was used as an optical LO signal to the EA waveguide OEM. Electrical voltage that contained the dc bias as well as the RF signal at $\omega_s = 1.0 \text{ GHz}$ was supplied to the device. The dc bias used was -0.75 V , which corresponds to the highest slope efficiency of the photocurrent versus dc bias curve. An RF circulator (bandwidth 1–2 GHz) was inserted between the device under test and the RF spectrum analyzer to measure the RF power generated at the device.

Fig. 3 summarizes the measurement results. The optical LO power incident on the EA waveguide was 10 mW; the input RF power was -20 dBm . The LO was observed at 900 MHz, and the signal at 1.0 GHz. Up-converted signal power detected at 1.9 GHz was -38.9 dBm after accounting for the microwave cable losses. In Fig. 3, other RF signals are also evident, e.g., second harmonics of the LO at 1.8 GHz; down-converted signal at 0.1 GHz; third-order intermodulation distortions (IMD₃) of the LO and the RF signal at 0.8 GHz, etc. The up- and down-converted signals appear to have different RF power, caused by the bandwidth limitation of the circulator. When the RF signal power was increased to -10 dBm , the converted signal powers

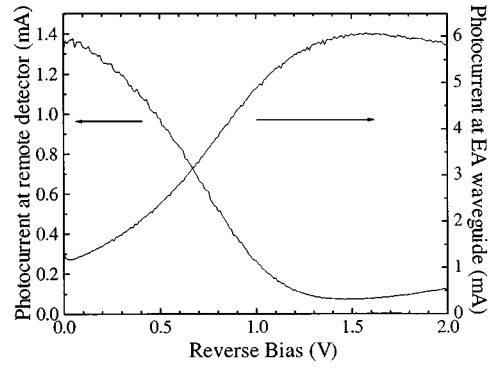


Fig. 1. Transmission (photocurrent at remote detector) and absorption (photocurrent at modulator) characteristics of the EA waveguide used in the experiment. Optical power of 10 mW at $1.319 \mu\text{m}$ is used. The normalized slope efficiency is -1.1 V^{-1} for transmission.

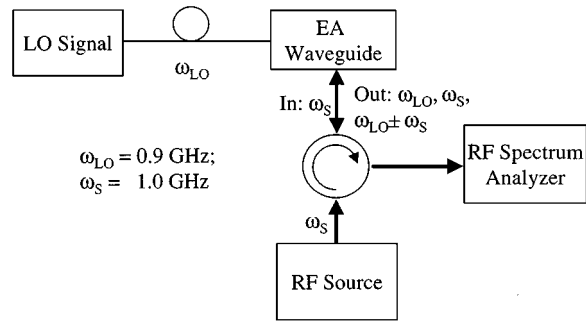


Fig. 2. Experimental set-up for the mixing experiment.

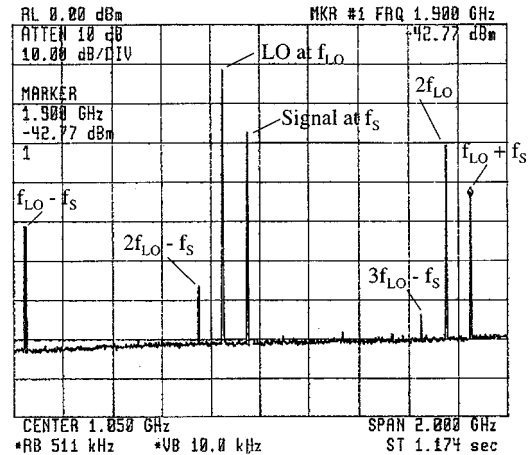


Fig. 3. Measured RF spectrum at the EA waveguide.

increased by 10 dB, closely following the prediction by (1). We found that the device tested became saturated around 10-mW LO optical power. Compared with the measurement at low optical power (1 mW), the RF link gain comprised of this EA waveguide as an external modulator was compressed by 4 dB at 10 mW. All the RF powers measured during these experiments matched theoretical values within 3 dB as long as saturation effects and component microwave losses were taken into account.

From the measured results, the conversion gain in this experiment is -18.9 dB . The conversion gain is mainly limited by LO optical power and the saturation power of the EA waveguide used. It can be improved by using an EA waveguide with higher

saturation, as increasing the LO power can increase the converted RF power, in accordance with (1). Decreasing the coupling loss from the fiber to the EA waveguide is another approach, which also increases η_m . When this EA waveguide was used as a modulator/mixer and the converted signals were transmitted through the optical fiber as in [4]–[6], the conversion gain was reduced to -27.8 dB. The 8.9-dB gain reduction is due to the fact that the responsivity of the remote detector, η_d at the end of the fiber link combined with the EA waveguide insertion loss, t_{ff} , was much smaller than that of the EA waveguide η_m , i.e., $t_{ff}\eta_d < \eta_m$.

The two-tone SFDR of the EA waveguide photodetector/RF mixer was also measured, as shown in Fig. 4. With the two RF tones at 1.00 and 1.02 GHz and the optical LO tone at 0.90 GHz, the converted signals and their IMD₃'s were measured. (Due to the bandwidth limitation of the circulator, up-converted signals were measured. A diplexer could be used to measure the down-converted signals.) When the EA waveguide was biased at the highest slope point of the device photocurrent versus dc bias curve (second-order null point), a suboctave SFDR of 102.4 dB-Hz^{2/3} was obtained at 10-mW optical LO power for the up-converted signal at 1.90 GHz. The noise floor was dominated by the shot noise due to the device photocurrent. When the EA waveguide was biased at the third-order null point of the device photocurrent versus dc bias curve (0.44 V), the up-converted RF signal power was reduced by ~ 3 dB, but the suboctave SFDR was measured at 120.0 dB-Hz^{4/5}. At the third-order null point, the IMD₃ due to the third-order input power dependence becomes null, making the IMD₃ depending on the next order, which is the fifth-order [4], [12]. The bias sensitivity for the third-order null point was ~ 10 mV. For narrow band applications, the second- and the fourth-order intermodulation distortions can be ignored as they are outside the passband. To the authors' knowledge, this SFDR result is among the best ever reported in the semiconductor-based approach, and compares favorably with the best SFDR in the other approach [6], considering the optical LO power used. The SFDR can be improved further by improving the saturation power of the waveguide.

A bulk EA waveguide that uses the Franz-Keldysh effect was also tested for RF signal conversion. Smaller conversion gains were measured at the same optical LO power at 10 mW, than those obtained with MQW waveguides. This result is mainly due to the smaller slope efficiency of the bulk EA waveguide and demonstrates the importance of the slope efficiency of the EA waveguide when it is utilized as a photodetector/mixer.

IV. CONCLUSION

We have demonstrated for the first time that the EA waveguide can be utilized as an OEM that combines both functions of a photodetector and an electronic mixer. Conversion loss and dynamic range have been measured for this OEM device. At 10-mW LO power, a suboctave SFDR of 120.0 dB-Hz^{4/5} was

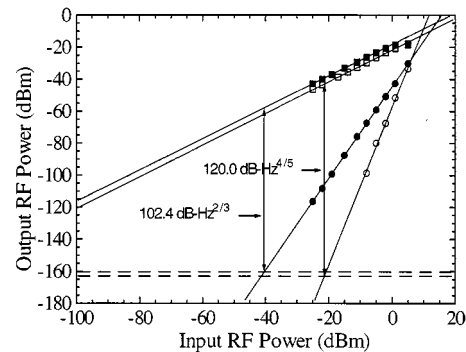


Fig. 4. Two-tone test of the MQW EA photodetector/RF mixer. Converted RF signals for the highest slope point (■) and the third-order null point (□), and the IMD₃'s for the highest slope point (●) and the third-order null point (○) are shown. Noise floors (dotted lines) were dominated by the shot noise and given by -160 and -163 dBm/Hz for the highest slope point and the third-order null point, respectively.

measured. We found that the slope efficiency of the EA waveguide is extremely important in determining conversion gain. Currently, -18.9 -dB conversion gain has been obtained and this can be improved with higher optical power.

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