Remote Optoelectronic Frequency Down-Conversion Using 60-GHz Optical Heterodyne Signals and an Electroabsorption Modulator

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***Abstract*—A new optoelectronic frequency down-conversion method for radio-on-fiber (RoF) uplink transmission is demonstrated by using an electroabsorption modulator, which down-converts uplink millimeter-wave signals into optical intermediate frequency (IF) using remotely fed optical local oscillator signals. Using this optoelectronic frequency down-converter, an RoF uplink is demonstrated in which quadrature-phase-shift keying uplink data signals in 60-GHz band are frequency down-converted to the 500-MHz optical IF signals and transmitted to the central station.**

***Index Terms*—Electroabsorption modulator (EAM), microwave photonics, millimeter-wave frequency conversion, optoelectronic frequency down-conversion, radio-on-fiber (RoF) systems, uplink transmission, wireless communications.**

I. Introduction

With the rapid progress in wireless communication technology, the demand for wireless broad-band data transmission has increased very much. As one promising candidate, millimeter-wave radio-on-fiber (RoF) systems have attracted much attention [1]–[9]. To implement these systems successfully, base stations have to be simple and cost-effective since many base stations are needed due to high transmission loss of millimeter-wave carriers and millimeter-wave components are expensive. Electroabsorption modulator (EAM) transceivers allow the simple antenna base station architecture for bidirectional RoF links because EAM can perform the dual functions of photodetection and optical modulation [1]–[3]. However, direct EAM modulation of uplink millimeter-wave signals generates double-sideband optical signals, which suffer the dispersion-induced signal fading problem in single-mode fiber [4]–[7]. Low-frequency intermediate frequency (IF) optical signal transmission can solve this problem. However, expensive millimeter-wave mixers and phase-locked local oscillators (LOs) are needed for frequency down-conversion from millimeter-wave frequency to IF. To eliminate this problem, various frequency down-conversion schemes using EAM have been introduced [5]–[7].

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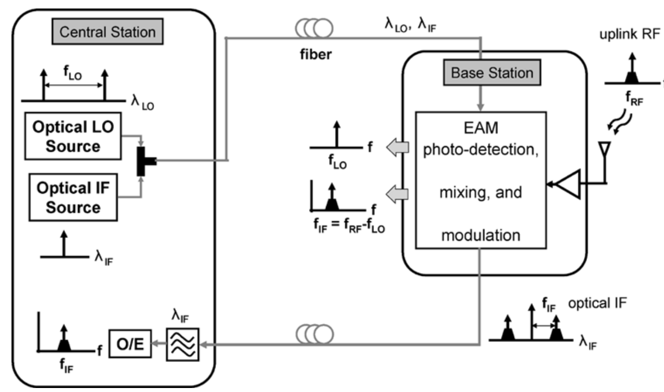

Fig. 1. Schematic explanation for the proposed frequency down-conversion technique.

In this letter, we propose a new EAM-based optoelectronic millimeter-wave frequency down-conversion method for IF-band optical uplink transmission. Using remotely-fed millimeter-wave optical heterodyne LO signals, the uplink millimeter-wave signals are optoelectronically frequency down-converted to the IF-band optical signals by EAM. With this technique, quadrature-phase-shift keying (QPSK) uplink data in 60 GHz are down-converted to optical IF and transmitted to the central station.

II. Principle of Optoelectronic Frequency Down-Conversion

Fig. 1 schematically shows the operation principle of our optoelectronic frequency down-conversion scheme. To obtain LO signals, the optical heterodyne technique is used. When optical heterodyne signals at $\lambda_{\rm LO}$ from the central station are injected into the EAM at the base station, photocurrents having $f_{\rm LO}$ are generated inside EAM by photodetection process. As a result, modulation frequency components to EAM have both externally applied $f_{\rm RF}$ and optically generated $f_{\rm LO}$. Due to the nonlinearities of EAM, optoelectronic mixing products at $f_{\rm IF} = f_{\rm RF} - f_{\rm LO}$ are produced, resulting in frequency down-converted IF signals [5]. These IF signals modulate the uplink optical carrier at $\lambda_{\rm IF}$, which is then transmitted to the central station without suffering the dispersion-induced signal fading problem. Effectively, a single EAM device is acting as a multifunctional device which simultaneously performs photodetection, frequency down-conversion, and uplink optical IF signal modulation.

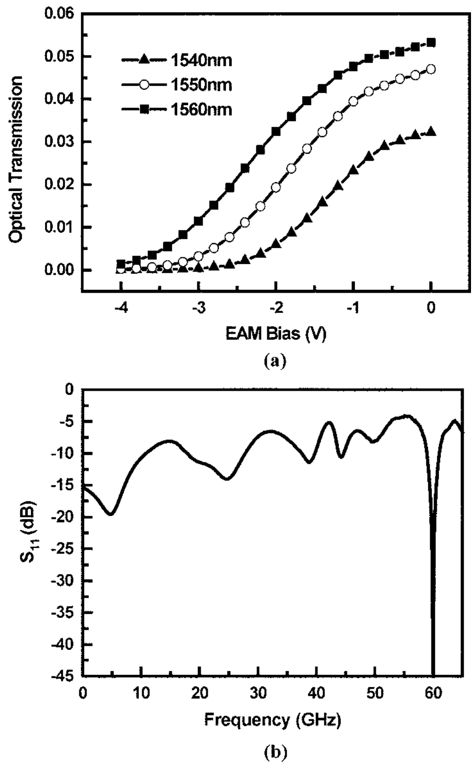

Fig. 2. (a) Optical transmission characteristics as a function of bias voltages of 60-GHz EAM. (b) S_{11} parameter response measured at EAM RF modulation port.

Using this optoelectronic frequency down-conversion method, expensive millimeter-wave-band phase-locked oscillators and mixers can be eliminated at the base station. Moreover, optical LO signals from the central station can be shared by several base stations and different $\lambda_{\rm IF}$ can be used for different base stations as long as $\lambda_{\rm IF}$ is within the EAM modulation range. Using these advantages, wavelength-division-multiplexing (WDM) technologies can be easily adopted in uplink RoF systems.

III. Experiment and Results

The EAM used in this experiment has a multiple-quantum-well structure and is packaged for 60-GHz narrow-band application. Details of EAM characteristics can be found in [9]. Fig. 2(a) shows the optical transmission characteristics of the packaged EAM as a function of bias voltages at different input wavelengths. The insertion loss for 0-V bias is about 11 dB at $\lambda = 1550$ nm. Fig. 2(b) shows measured S_{11} parameter characteristics at the input radio frequency (RF) modulation port. As can be seen in the figure, S_{11} parameter values near 60 GHz are very small with bandwidth of about 2 GHz.

Fig. 3 shows the experimental setup for the 60-GHz optoelectronic frequency down-conversion experiment. The 59.5-GHz optical heterodyne LO signals were generated by a Mach–Zehnder modulator biased at the minimum transmission point with 29.75-GHz signal. An erbium-doped fiber amplifier was used after the Mach–Zehnder modulator. For the uplink optical carrier, a distributed feedback laser at $\lambda_{\rm IF} = 1552.5$ nm was used. These two signals were combined by a 3-dB coupler and injected into the EAM. For generating 60-GHz uplink

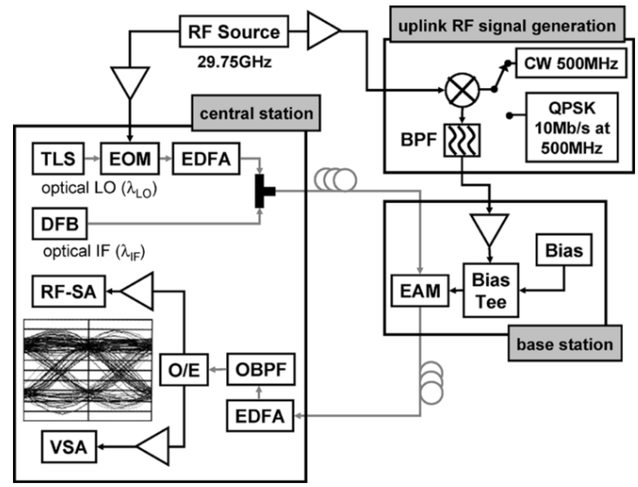

Fig. 3. Experimental setup for 60-GHz frequency down-conversion and uplink data transmission. TLS: Tunable laser source. DFB: Distributed feedback laser diode. EOM: Electrooptic modulator. EDFA: Erbium-doped fiber amplifier. BPF: Bandpass filter. OBPF: Optical bandpass filter. RF-SA: RF spectrum analyzer. VSA: Vector signal analzyer.

RF signals, a subharmonic RF mixer was used. For IF signal source, either continuous-wave signals at 500 MHz or 10-Mb/s QPSK data signals at 500 MHz were used. After the RF mixer, an RF bandpass filter was placed for reducing image signals from the mixer. The resulting 60-GHz signals were applied to the EAM after passing an amplifier and a bias-T. At the central station, a 20-dB gain erbium-doped fiber amplifier was used to compensate the insertion loss of the EAM, and an optical attenuator was placed not to exceed the photodiode saturation optical power. An optical bandpass filter was also used so that unwanted optical heterodyne LO signals could be suppressed. In the present investigation, all the measurements were done in back-to-back conditions.

Fig. 4(a) shows an example of the RF spectrum for frequency down-converted IF signals at the central station. For this measurement, 5-dBm optical LO signals at 1550 nm and 0-dBm optical IF carriers at 1552.5 nm were applied to the EAM biased at -1.8 V. The input RF power of the uplink signal was 5 dBm. To find the optimum bias point for optoelectronic frequency down-conversion, down-converted 500-MHz RF powers were measured at several EAM biases. The wavelengths of optical heterodyne LO signals were also changed from 1540 to 1560 nm. The EAM input optical and RF powers were the same as above. Fig. 4(b) shows the measurement results. It can be observed that the LO wavelength dependence is pronounced for large biases. Overall, the bias condition for the maximum frequency down-conversion RF power corresponds to the bias which provides the maximum modulation efficiency, or the largest slope in modulation characteristics shown in Fig. 2(a). All this is believed due to wavelength and bias dependence of nonlinear characteristics of EAM, but further investigations are needed.

Finally, 60-GHz band uplink data transmission was demonstrated. For the IF data transmission, 10-Mb/s QPSK data at 500 MHz were generated from a QPSK signal generator and frequency up-converted to 60 GHz by a subharmonic mixer. Fig. 5(a) shows the QPSK data spectrum at the 60-GHz band before applied to EAM. This signal was frequency down-converted by the EAM and transmitted to the central station on

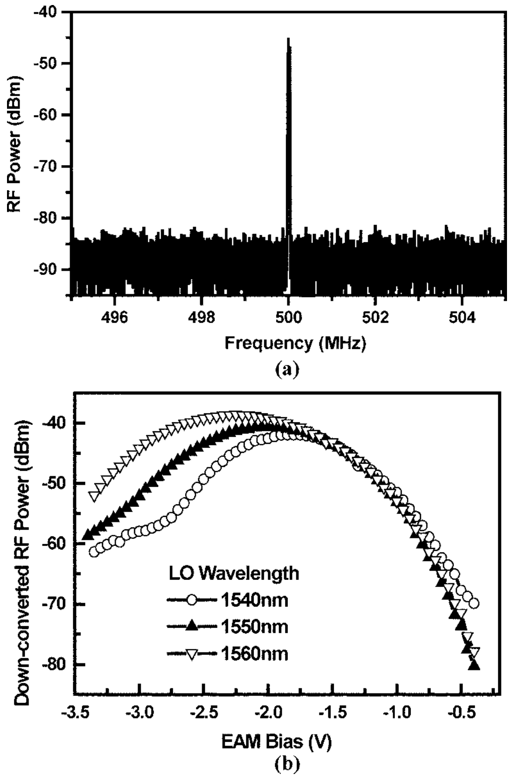

Fig. 4. (a) Frequency down-converted 500-MHz IF signal spectrum. Resolution bandwidth is 10 kHz. (b) Frequency down-converted signal power as a function of EAM bias voltages at different optical heterodyne signal wavelengths.

1552.5-nm optical IF carrier. Optical heterodyne LO signals at 1560 nm were used and the EAM was biased at −2 V for efficient frequency down-conversion as determined from Fig. 4(b). Fig. 5(b) shows the spectrum of 500-MHz QPSK data transmitted to the central station. The received QPSK data were analyzed with a vector signal analyzer. The error vector magnitude was about 14.7%, which corresponds to the signal-to-noise ratio of 16.6 dB. The eye diagram for the resulting demodulated signals was inserted in Fig. 3. It should be noted that much higher data rate transmission as well as other data modulation methods should be possible with our scheme, but in this feasibility experiment, only 10-Mb/s QPSK data transmission was possible due to limited equipment available to us. Although results only for up-link transmission are reported in this letter, bidirectional RoF links can be easily realized combining the present down-conversion technique with other up-conversion techniques. Results of our initial investigation are reported in [9].

IV. Conclusion

We investigated a new optoelectronic frequency down-conversion method using remotely fed 60-GHz optical heterodyne LO signals and EAM nonlinearities. The EAM performs frequency down-conversion as well as photodetection and optical modulation. With this technique, it is possible to produce IF-band optical signals without using electrical phase-locked oscillators and mixers at the base station. Moreover, optical heterodyne LO signals can be shared by several base stations and the use of separate uplink wavelength makes it possible to apply WDM techniques to uplink RoF systems. In our feasibility demonstration, up-link transmission of 10-Mb/s QPSK data in 60 GHz was successfully demonstrated.

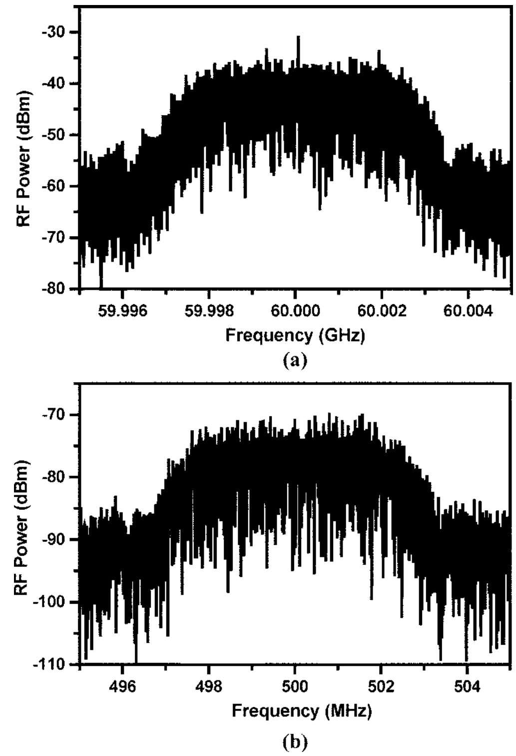

Fig. 5. (a) The 10-Mb/s QPSK modulated signal spectrum at 60 GHz. (b) Frequency down-converted QPSK modulated signal spectrum at 500 MHz. Resolution bandwidth is 100 kHz.

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