

All-Optical Subcarrier Frequency Conversion Using an Electrooptic Phase Modulator

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Abstract—All-optical subcarrier frequency conversion using an electrooptic phase modulator in a radio-over-fiber link is proposed and demonstrated. The frequency mixing is implemented by an electrooptic phase modulator, to which a local oscillator frequency is applied. The phase modulation to intensity modulation conversion is realized by using a length of single-mode fiber, which serves as a dispersive device. A subcarrier frequency conversion from 3 to 11.5 GHz performed over a 25-km radio-over-fiber link is experimentally demonstrated.

Index Terms—All-optical microwave mixing, chromatic dispersion, electrooptic phase modulation (PM), radio-over-fiber, single-mode fiber (SMF), subcarrier frequency conversion.

I. INTRODUCTION

DISTRIBUTION of radio signals over optical fiber or radio-over-fiber is of great interest for many applications such as broad-band wireless access networks, sensor networks, radar, and satellite communications and has been intensively investigated in the last few years [1]–[3]. The primary function of a radio-over-fiber network is to distribute radio signals over optical fiber, by taking the advantages of the low loss, wide-band, light weight, and immunity to electromagnetic interference offered by optical fibers. Radio-over-fiber networks using subcarrier multiplexing (SCM) provides the advantages of low cost and high bandwidth efficiency by distributing multiple channel radio signals over a single optical wavelength. A great number of papers have been published in the last few years reporting SCM technologies for radio-over-fiber applications [4]–[8]. To implement subcarrier frequency conversion, Nasu *et al.* [4] proposed to use an optically repeated SCM system to distribute video signals. Since optical-to-electrical (O/E) and electrical-to-optical (E/O) conversions were required, the system was complicated and costly. Although approaches for all-optical mixing of microwave signals based on a laser diode has been intensively investigated in the last few years [9], [10], the approaches are not suitable for subcarrier frequency conversion, since the signals to be mixed at the laser diode are electrical signals and must be located at the same site. For subcarrier frequency conversion, however, the subcarrier signal is already in the optical domain and the local oscillator signal may be located at a different site. In addition, the modulation frequency of a laser diode is usually

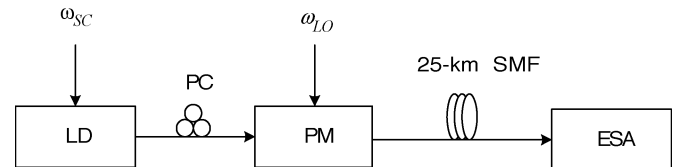


Fig. 1. All-optical subcarrier frequency conversion using a phase modulator and a length of SMF. LD: laser diode. PM: phase modulator. ESA: electrical spectrum analyzer.

limited to less than 10 GHz. For next-generation wireless access networks using radio-over-fiber technology, the subcarrier frequency would be in the millimeter-wave bands. In this situation, a high-speed external modulator must be used to convert the subcarrier from a low frequency to a high frequency. To implement subcarrier frequency conversion without O/E and E/O conversions, in this letter, we propose a novel approach that uses an electrooptic phase modulator in combination with a length of single-mode fiber (SMF) to achieving all-optical subcarrier frequency conversion. The electrooptic phase modulator is used to perform all-optical microwave mixing. The phase modulation (PM) to intensity modulation (IM) conversion is then implemented using the SMF serving as a dispersive device. The use of the proposed all-optical system to perform subcarrier frequency conversion from 3 to 11.5 GHz in a 25-km radio-over-fiber link is demonstrated.

II. PRINCIPLE

The block diagram of the proposed all-optical subcarrier frequency conversion system is shown in Fig. 1. The system consists of a laser diode, an electrooptic phase modulator, and 25-km standard SMF. The subcarrier at a low microwave frequency ω_{SC} is applied to the laser diode. The modulated signal is then fed to the electrooptic phase modulator, to which a local oscillator frequency ω_{LO} is applied. All-optical mixing of the microwave signals is implemented at the phase modulator. The output signal from the phase modulator is then sent to a remote site via the 25-km SMF. There are three functions of the 25-km SMF. First, it acts as a dispersive device to convert the phase modulated signal to an intensity modulated signal. Second, the transfer function of the PM in conjunction with the SMF is equivalent to a bandpass filter; mixing frequency components outside the bandwidth will be rejected. Third, it serves as a transmission medium to distribute the frequency converted subcarrier signal to a remote site.

In the proposed system, the direct modulation of the laser diode and then the PM will generate various optical sidebands. The frequency deviations from the optical carrier ω_{opt} are $\pm\omega_{SC}$, $\pm\omega_{LO}$, $\pm 2\omega_{SC}$, $\pm 2\omega_{LO}$, ..., and

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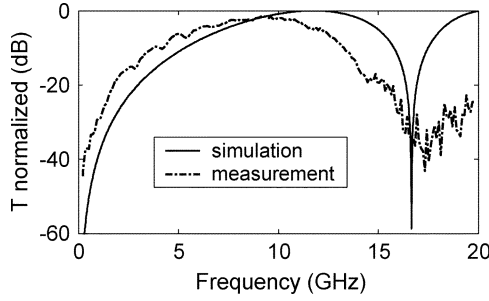


Fig. 2. Transfer function of the PM to IM conversion using 25-km standard SMF.

$\omega_{SC} \pm \omega_{LO}, 2\omega_{SC} \pm \omega_{LO}, \omega_{SC} \pm 2\omega_{LO}, \dots$. Assuming that the modulation depth is small, frequency conversion at $\omega_{SC} + \omega_{LO}$ mainly comes from the beating of the spectral lines $\omega_{opt} + \omega_{SC}$ with $\omega_{opt} - \omega_{LO}$, $\omega_{opt} - \omega_{SC}$ with $\omega_{opt} - \omega_{LO}$, $\omega_{opt} + \omega_{SC} + \omega_{LO}$ with ω_{opt} , and $\omega_{opt} - \omega_{SC} - \omega_{LO}$ with ω_{opt} . Beatings from higher order sidebands are very small and can be ignored.

In our case, frequency modulation (FM) of the laser diode is dominant over IM (distributed feedback laser diode with a high enhancement factor of five). In this condition, it can be derived that the sum, listed above, of the contributions of the four beating terms generating mixing frequency $\omega_{SC} + \omega_{LO}$ is null. So, if this signal from the phase modulator is directly detected using a photodetector, no mixing signals between the subcarrier with the local oscillator signal will be detected. Only the intensity modulated microwave signal generated at the laser diode will be detected. However, if the optical signal passes through a dispersive device, for example, a length of SMF, the phase relationship between all spectral lines will be changed to fully or partially in phase, thanks to the chromatic dispersion of the fiber. FM of the laser diode and PM are then converted to IM. When the converted signals are fed to a photodetector, mixing signals at $\omega_{SC} + \omega_{LO}$ will be obtained.

Mathematically, the PM to IM conversion using a length of SMF can be expressed by

$$H(\omega_m) = A \cos\left(\frac{\pi D L \lambda_0^2 \omega_m^2}{4\pi^2 c} + \frac{\pi}{2}\right) \quad (1)$$

where c is the speed of light traveling in free space; D is the dispersion parameter which is 17 ps/nm · km for standard SMF operating at 1550 nm; L is the length of the SMF; λ_0 is the wavelength of the optical carrier; ω_m is the frequency of the modulation signal; and A is a constant depending on the losses of the fiber and the phase modulator. For the system using a phase modulator and 25-km SMF, the total optical loss is about 7 dB. The transfer function of the PM to IM conversion with intensity detection by a photodetector is shown in Fig. 2. It can be seen that the transfer function is equivalent to a bandpass filter.

III. EXPERIMENT

The PM to IM using the 25-km SMF is first experimented. The measured transfer function of the conversion is shown in Fig. 2. It can be seen that the simulated and the experimental transfer functions agree well at frequencies lower than 10 GHz. A mismatch is observed for frequencies higher than 10 GHz,

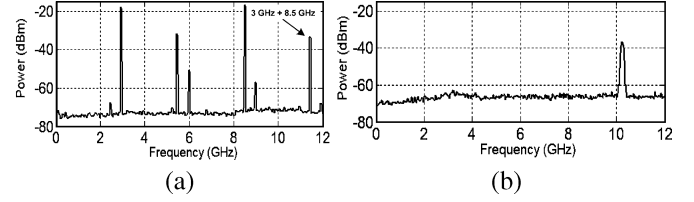


Fig. 3. Spectra at the output of the photodetector. (a) Up-converted subcarrier at 11.5 GHz; (b) up-converted subcarrier at 10.4 GHz with a 100-Mb/s BPSK signal modulated. Other frequency components are eliminated after bandpass microwave filtering.

which is due to the limited bandwidth of the phase modulator. The central frequency of the bandpass filter is around 10 GHz. The lower 3-dB frequency f_{mMin} is 6.2 GHz and the higher 3-dB frequency f_{mMax} is 12 GHz. The 3-dB bandwidth of the bandpass-equivalent filter is 5.8 GHz.

Then, we experiment with the subcarrier frequency conversion. In the experimental setup, a laser diode emitting at 1550 nm with an output power of 3.58 mW is used. A 3-GHz microwave signal with 3-dBm power is applied to directly modulate the laser diode. The output from the laser diode is then applied to the input of a JDS-U phase modulator. To up-convert the subcarrier frequency, a local oscillator signal with an output power of 18 dBm is applied to the RF port of the phase modulator. The output from the phase modulator is connected to a 25-km standard SMF to achieve PM to IM conversion. The PM-to-IM converted signal is then detected by a photodetector. When the frequencies of the local oscillator signal are tuned at 4, 8.5, 9.5, and 12.5 GHz, frequency up-converted signals are observed at 7, 11.5, 12.5, and 15.5 GHz, respectively, with output powers of -41 , -32.5 , -33.5 , and -40.5 dBm. It can be seen that the power at 11.5 GHz is higher than those at the other frequencies. This is because the phase-to-intensity-modulation conversion is equivalent to a bandpass filter with a central frequency at around 10 GHz.

The analog electrical spectrum at the output of the photodetector is shown in Fig. 3(a), in which the local oscillator signal frequency is $f_{LO} = 8.5$ GHz. A strong frequency up-converted subcarrier at 11.5 GHz is observed. The power level of the up-converted subcarrier signal is -32.5 dBm with a signal-to-noise ratio better than 30 dB. The conversion losses of the system, defined as the ratio between the power of the up-converted signal and the power of the signal detected at the output of the laser diode at frequency f_{RF} , is measured to be -23 dB, which is in the same range as for classical optical microwave mixing techniques [10].

An experiment on the system performance with data modulation is also performed. Fig. 3(b) shows the spectrum of an up-converted 100-Mb/s binary phase-shift keying (BPSK) from $f_{RF} = 5.5$ GHz to $f_{RF} + f_{LO} = 10.4$ GHz. Other frequency components except around 10.4 GHz are eliminated with a narrow bandpass microwave filter. Three different bit rates are tested: 100 Mb/s, 500 Mb/s, and 1 Gb/s. The bit-error rate (BER) is measured after a coherent demodulation at 10.4 GHz. The experimental results are presented in Fig. 4. The frequency components other than the up-converted subcarrier could also be removed with ultranarrow-band optical filters, such as equivalent-phase shifted fiber Bragg grating filters [11] or all-optical microwave filters [12].

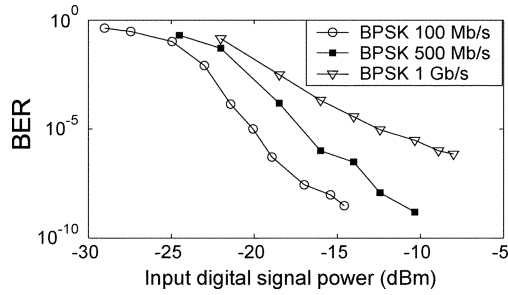


Fig. 4. BER measured at the output of the photodetector after demodulation.

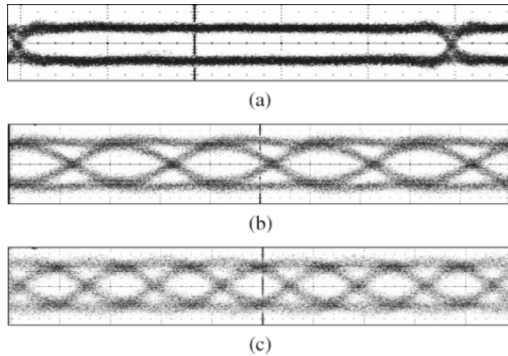


Fig. 5. Eye diagrams of the demodulated BPSK digital signal at (a) 100 Mb/s, (b) 500 Mb/s, and (c) 1 Gb/s.

An error-free up-conversion of a 100-Mb/s BPSK signal is obtained for input BPSK power higher than -13 dBm. A BER of 10^{-9} is obtained for a BPSK signal at 500 Mb/s with an input power of -10 dBm and 10^{-6} at 1 Gb/s with an input power of -8 dBm. Fig. 5 shows eye diagrams after demodulation of the up-converted BPSK signals at 10.4 GHz, with $f_{RF} = 5.5$ GHz and $f_{LO} = 4.9$ GHz. The eye diagrams for 100 and 500 Mb/s are clear and widely opened, demonstrating that an error-free up-conversion is reached. For bit rates higher than 500-Mb/s signal, spectra of up-converted BPSK signals at 11 GHz (twice the input frequency $f_{RF} = 5.5$ GHz) and at 10.4-GHz overlay which causes errors in data transmission. This overlaying explains the error-floor measured for the 1-Gb/s up-converted BPSK signal, as shown on Fig. 4. For no interference between the main band of the up-converted BPSK signal spectra, it can be easily derived that the maximum BPSK data rate is $D_{max} = |f_{RF} - f_{LO}| = 600$ Mb/s. It can be noticed that this maximum data rate of 600 Mb/s could be improved with better choice of input frequencies.

IV. DISCUSSIONS AND CONCLUSION

We have proposed and demonstrated an all-optical subcarrier frequency conversion system using a phase modulator in combination with a length of standard SMF. Thanks to the chromatic dispersion of the SMF, the phase modulated signals were converted to intensity modulated signals. In addition, the transfer function of the phase-to-intensity conversion was equivalent to a bandpass filter, for mixing frequencies outside the passband would be rejected. The central frequency of the bandpass-equivalent filter was about 10 GHz when the length of the standard SMF was 25 km and the operating optical wavelength was at 1550 nm. To convert subcarrier frequency

to millimeter-wave band frequencies, the central frequency of the equivalent passband should be much higher, which would require a much smaller chromatic dispersion. A way to achieve a specific central frequency for a fixed transmission distance is to control the accumulated chromatic dispersion. One solution is to include a chirped fiber Bragg grating with a negative chirp rate into the transmission link to obtain the desired accumulated chromatic dispersion. One added advantage of using the SMF for phase-to-intensity-modulation conversion is that the frequency-converted subcarrier signal is not only generated, but also distributed to a remote site. In addition, it is different from optical transmission systems using direct modulation or external IM, the chromatic dispersion of optical fiber will lead to power penalty at high frequencies, which limits the transmission distance. For the proposed system, the chromatic dispersion of the fiber is a positive factor which not only ensures a phase-to-intensity-modulation conversion, but also provides a passband functionality that filters out, to some extent, the unwanted mixing frequency components. Experimental results have shown that a frequency-upconverted subcarrier signal was obtained at the other end of a 25-km fiber with high signal quality.

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