Low Noise Photonic Millimeter-Wave Generation Using an Integrated Reciprocating Optical Modulator

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***Abstract*–We generated low-phase-noise millimeter waves by using a reciprocating optical modulator. A lightwave modulated by a 44-GHz millimeter wave was obtained from a microwave signal, with a phase noise of –88.5 dBc/Hz at an offset of 10 kHz. The intensity of the millimeter waves generated was quite stable, and the linewidth was less than 1 Hz. The noise figure obtained in our reciprocating modulation process was lower than the theoretical limit for conventional frequency multipliers.**

***Index Terms*–Millimeter wave, multiplication, optical filter, optical modulation, phase noise.**

I. Introduction

OPTICAL modulation in millimeter-wave bands is a key technology in radio-on-fiber technology and radio astronomy [l], [2]. Traveling-wave optical modulators are often used to obtain broad-band optical responses up to the millimeter-wave region [3]. Resonant-type modulators can also be used to obtain effective optical modulation in a particular band [4] , Recently, we proposed a novel optical modulation technique that enables effective generation of high-order optical sideband components by using two optical filters placed at the optical input and output ports of an optical phase modulator [5], [6]. By using this technique, called reciprocating optical modulation (ROM), we can generate a lightwave modulated by a radio-frequency (RF) signal whose frequency is the integer multiple of that of the electric RF signal applied to the modulator. Thus, we can use a low-cost microwave-signal source to drive the modulator. In ROM, some of the sideband components are fed to the optical phase modulator again, to effectively generate specific sideband components. The desired sideband components are taken out of the modulator, without recycling to generate the harmonics. This is in contrast to mode-locked lasers and optical comb generators, where all generated sideband components are recycled into the modulators regardless of the optical frequency [7]. Thus, the desired sideband components are effectively enhanced, without spreading the optical power over undesired sideband components. By feeding the output lightwave to a high-speed photodetector, we can generate a stable millimeter wave without using any feedback stabilization systems. This letter demonstrates low-phase-noise photonic millimeter wave generation using ROM. We used an ingegrated modulator consisting of two optical filters and an optical phase modulator, where the filters were fixed in V-grooves on SiO_2 substrates. The optical path length between the filters was highly constant, so that we can obtain stable and low noise millimeter wave without using feedback stabilization techniques. *U*-band millimeter-wave signals were generated from 2.2- or 4.4-GHz microwaves. The phase noise ratio between source and generated signals was less than 20 log *N* which is the theoretical limit in conventional frequency multipliers, where *N* is the order of harmonic generation.

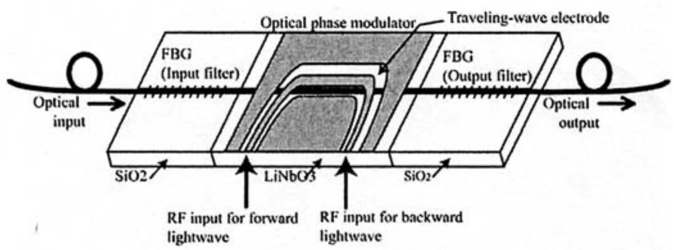

Fig. 1. ROM. The modulator chip was butt-jointed with the filters fixed on SiO_2 substrates, where the lengths of the gratings, the traveling-wave electrodes, and the modulator chip were. respectively, 15, 38, and 56 mm. The distance between tbe joint and the center of the grating was 12.5 mm.

II. ROM

As we can see from the schematic in Fig. 1, an ROM consists of two optical filters (henceforth, output and input filters) and an optical phase modulator put between them. The two filters are fiber Bragg gratings (FBGs), which are almost equal in center frequency and bandwidth. Consider that input lightwave frequency is close to the lower edge of the refiection band, and that sinusoidal RF electric signals (henceforth, driving signal) are fed to both the input and output electric ports of the modulator, with zero phase difference. The sideband components, generated from the input lightwave by the optical phase modulator, are reflected by the output filter and fed into the modulator again. The lightwave reciprocates several times as previously described. Finally, the desired spectral components near the higher edge of the reflection band are generated after several modulation steps, and they pass through the output filter without being recycled in the modulation process. Similarly, when the input lightwave frequency is close to the higher edge, we ca.n generate optical sideband components near the lower edge. The difference in frequency between the input lightwave and the generated sideband component is nearly equal to the reflection bandwidth of the filters. Thus, by feeding the optical output to a high-speed photodetector, we can generate electric signals whose frequency corresponds to the refiection bandwidth. To make all of the ROM steps be in-phase, the driving signal frequency should be $\tau^{-1} \times n$ (n = 1,2,3, . . .),

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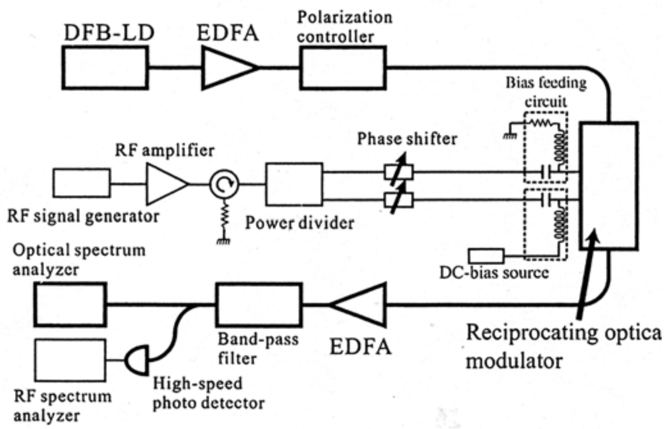

Fig. 2. Experimental setup.

where τ is the optical delay between successive modulation steps. In addition, when the driving signals for the forward and backward lightwaves are opposite in polarity, we can drive the ROM with a signal whose frequency is $\tau^{-1} \times (n + 1/2)$. The conversion efficiency of the *N*th order sideband is much larger than the *N*th power of the first-order sideband generation efficiency at the phase modulator [6]. This is due to constructive interference of a number of multiple modulation processes.

The optical phase modulator section of the fabricated ROM had a traveling-wave-type electrode on the *z*-cut $LiNbO_3$ substrate, whose halfwave voltage was 6.4 V. The output and input filters were fixed in V-grooves on the SiO_2 substrates. The center wavelength was 1552.6 nm (193.23 THz) and the bandwidth was 41.2 GHz, so that a millimeter-wave signal in the *U*-band could be generated from the photodetector. The FBGs were specially designed to have very narrow cutoff bands to achieve ROM driven by a low-frequency signal. A cutoff band is defined as a band where the reflectivity ranges from –0.5 to –3.0 dB. The lower limit of the driving signal frequency for ROM is dominated by the cutoff bandwidth. The bandwidth of the fabricated FBG was 2.5 GHz (40% of a conventional filter). The length of the modulator section was 56 mm and the refractive index was 2.2. The group delay in reflection at the FBG was 44 ps, so that delay τ was 454 ps = $(2.2\ \text{GHz})^{-1}$.

III. Experimental Results

Fig. 2 shows the experimental setup for photonic millimeter-wave generation using an integrated ROM. The frequencies of the driving signals were 2.2 and 4.4 GHz, where respective powers were 25.0 and 22.0 dBm at each RF input port of the modulator. DC-bias voltage was applied on the optical phase modulator to adjust the optical phase delay in the successive modulation steps. The input lightwave frequency was close to the lower edge of the refiection band. The optical power at the input port of the ROM was 6.3 dBm. The respective optical powers for 2.2 and 4.4 GHz driving at the output port of the ROM were –5.3 and –2.5 dBm. The output lightwaves were amplified by an erbium-doped fiber amplifier (EDFA), where the amplified spontaneous emission noise was reduced by a tunable bandpass optical filter comprised of a tunable FBG and an optical circulator. The bandwidth of the FBG was 46 GHz and its reflectivity was 30 dB. In the optical output, the spectral component corresponding to the input lightwave was also reduced to be equalized with the high-order sideband component generated by the reciprocating modulation process.

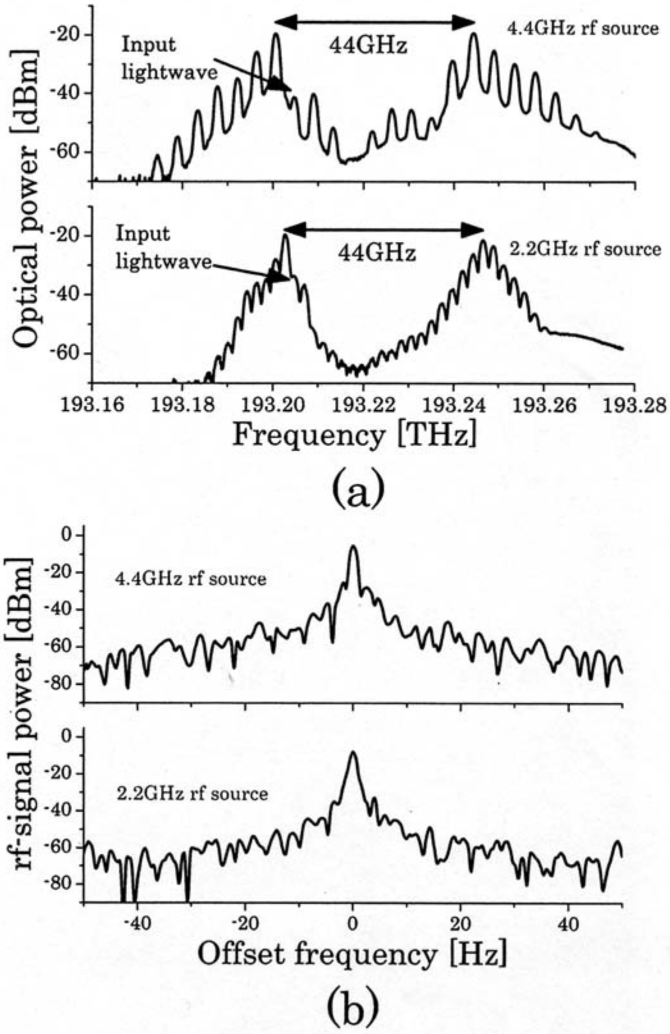

Fig. 3. Spectra of ROM output signals for 2.2-GHz driving (lower) and 4.4-GHz driving (upper). (a) ROM output optical spectra. Output lightwaves were amplified by an EDFA, and filtered by a tunable FBG. (b) Spectra of millimeter-wave signal obtained by photodetector, where resolution bandwidth of the spectrum analyzer (1 Hz) is dominant in bandwidths of measured spectra. Noise floor of the spectrum analyzer (Agilent 8565E) was – 117 dBm at 44 GHz.

The optical powers at the photodetector were 0.5 (2.2-GHz driving) and 4.5 dBm (4.4-GHz driving). As shown in Fig. 3(a), high-order optical sideband components were effectively generated near the upper edge of the band. Fig. 3(b) shows the spectra for generated millimeter waves of 44 GHz. The linewidths of the millimeter waves were less than 1 Hz. The intensity and frequency of the millimeter waves were stable without the use of any feedback stabilization techniques. As shown in Fig, 4, we also measured the power spectral density (PSD) of the 44-GHZ millimeter waves, and that of the source RF signals to drive the ROM, by using a spectrum analyzer (HP8565E) and a phase noise measurement utility (HP85671A). In thls letter, we defined the noise figure as the ratio between the PSD of the driving signal and that of the millimeter wave generated by the ROM. Fig. 5 plots the noise figures calculated from the measured PSDs. In conventional frequency multipliers, the lower theoretical limit of the noise figure is given by

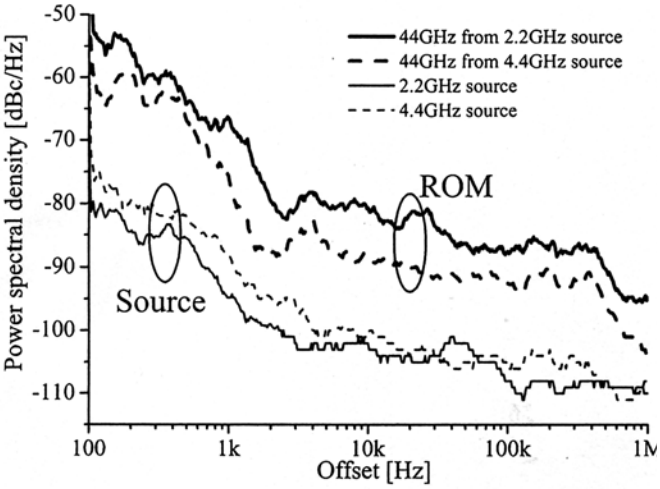

Fig. 4. PSDs of ROM-generated millimeter waves driven by 2.2- (solid line) and 4.4-GHz (dashed line) signals. Thin lines are for the driving signals generated by Wiltron 69 065A.

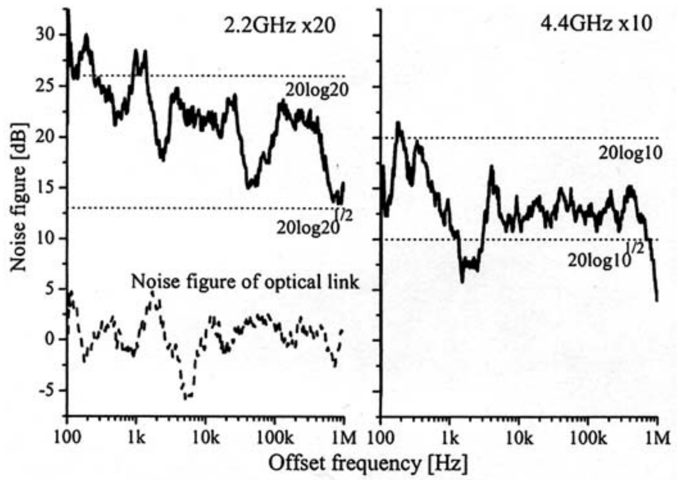

Fig. 5. Noise figures for ROM defined by the ratio between PSD of the driving signal and that of ROM-generated millimeter waves, where the frequencies of driving signals are 2.2 (left-hand) and 4.4 GHz (right-hand). Noise figure of the optical link is also plotted in the left-hand graph (dashed line).

20 log N dB, where N is the order of harmonic generation, because the fluctuations are magnified by N. This means the noise was coherently summed in the multiplication process. ROM, on the other hand, generates the harmonics in a series of successive modulation processes, so that the fluctuations in the phase or amplitude can be changed during the ROM procqss. We deduced that the fluctuations changing faster than the ROM processes were summed incoherently, and that the noise figure could be expressed by 20 log $\sqrt{N}$ dB, as in random walk vectors, As we can see in Fig. 5, the noise figures of the ROM were less than the conventional limit, and were close to 20 log $\sqrt{N}$ dB when the offset frequency was larger than 1 kHz. Phase fluctuatlon in low frequency region would be summed coherently, because the ROM process is faster than the change of the fluctuation. Thus, we can infer that the noise figure in small offset frequency should be close to the conventional limit (20 log N dB). On the other hand, the noise figure is a decreasing function of the offset frequency, and becomes close to 20 log $\sqrt{N}$ dB in large offset frequency, because phase fluctuation changes faster than, the optical delay in the whole ROM process. PSD consists of amplitude and phase noises. Phase noise is dominant in a source signal generated by a synthesizer. The PSD of ROM was lower than the conventional limit, so that we deduced that excess amplitude noise generated in ROM process was small, and that phase noise was also dominant in the millimeter waves generated by ROM. In addition, we also measured the noise figure of an optical link, to estimate the noise generated by the optical components shown in Fig. 2. We replaced the ROM by a conventional optical intensity modulator. A 44-GHz millimeter wave was fed to the modulator, and the optical output was applied to the photodetector via the optical amplifier and filter. The noise figure, which is the ratio between the PSDs of the RF source (44 GHz) and the RF signal demodulated by the photodetector, was much smaller than that of ROM, as shown in Fig. 5. Thus, the amplitude noise due to the optical components was negligible and we can assume that the PSD was almost equal to or slightly larger than the phase noise. As shown in Fig. 4, the phase noise of the 44-GHz ROM signal generated from 4.4-GHz signal was less –88.5 dBc/Hz at an offset of 10-kHz offset.

IV. Conclusion

We have demonstrated generation of millimeter waves in the U-band for radio-on-fiber systems by using an integrated ROM. Lightwaves with 44-GHz millimeter wave beat components were obtained from 2.2- and 4.4-GHz microwave signals. The spectrum linewidths of the millimeter waves were less than 1 Hz. The phase noise was lower than the theoretical limit for conventional frequency multipliers.

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