40 GHz Millimeter-Wave Signal Generation Using a Lattice-Form Mach-Zehnder Interferometer

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***Abstract*—We propose and study a new scheme for optical millimeter-wave generation using a lattice-form Mach-Zehnder interferometer (LF-MZI) designed in a planar lightwave circuit (PLC). Our simulations demonstrate that a LF-MZI with a conventional 10 GHz Mach-Zehnder modulator can generate a stable 40 GHz signal, suitable for a radio-over-fiber (ROF) link. By using an all-optical LF-MZI in the ROF link we can avoid a 20 GHz electrical signal generator and a dual-drive $LiNbO_3$ external modulator in the set-up. We compare the results with optical carrier suppression (OCS) technique with a dual-drive $LiNbO_3$ modulator.**

I. INTRODUCTION

Various methods of generation of the millimeter wave signals for radio-over-fiber (ROF) communication links has been developed recently [1-5]. Optically generated 40 GHz signal has been shown to transmit 2.5 Gb/s data from the central station to the base station [1-2]. The most advanced technique for this type of transmission is optical carrier suppression (OCS), where a dual-drive $LiNbO_3$ Mach-Zehnder modulator (D-LN-MZM) produces two tones separated by twice the drive frequency (20 GHz) and suppresses the carrier. The realization and development of these new networks requires a high-frequency dual-drive modulator and 20 GHz electrical signal generator. The cost of the link is therefore high and will increase drastically when DWDM approach will be introduced in the ROF networks [4]. It is therefore vital for the future development of ROF to reduce the cost of the link by finding new solutions which can use the main concept of OCS.

Pulse-repetition rate multiplication techniques may bring the desired solution for ROF networks as they are developed using available components, such as arrayed waveguide gratings, sampled fiber Bragg gratings, superimposed fiber Bragg gratings, and a Fabry-Perot etalon [5-7]. For example, pulse trains at 40 GHz were obtained from 10 GHz pulse trains using a periodic filter with a sinc-shape [7]. It has been shown recently that a 40 GHz pulse train may be generated from a 10 GHz pulse using an all-optical planar lightwave circuit (PLC) -based spectrally-periodic filter [8-9]. The 4-stage lattice-form Mach-Zehnder interferometer (LF-MZI) filter was designed using direct temporal domain approach and fabricated in Ge-doped silica-on-silicon [8-9]. Although the LF-MZI has been shown to generate 40 GHz output with a binary amplitude codes, this device has never been used yet for the generation of the 40 GHz signal for the ROF downlink. In this paper for the first time we present the modeling data of a new ROF scheme which uses LF-MZI for the generation of a millimeter-wave signal, subsequent modulation with 2.5 Gb/s pseudo-random bit sequence (PRBS) signal, and transmission over the downlink.

II. MILLIMETER WAVE GENERATED BY LF-MZI

The diagram of the proposed set-up is shown in Fig. 1. The optical CW lightwave is generated by a distributed feedback (DFB) laser (5 mW at 1550 nm) and is modulated by a MZM-1 at 10 GHz with a uniform bit sequence {1111}. The generated optical signal then passes through the LF-MZI.

The LF-MZI, shown in Fig. 2, has three Mach-Zehnder interferometer (MZI) filters (stages) connected with four 3dB couplers. The optimized phase shifts of $\varphi_i = \{1.5; 1.5; 0\} \times \pi$,

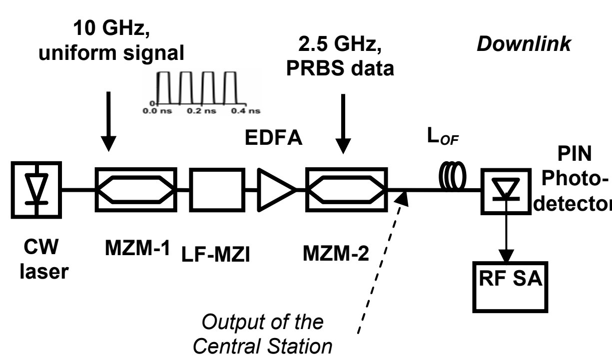

Figure 1. Schematics of the ROF link with LF-MZI.

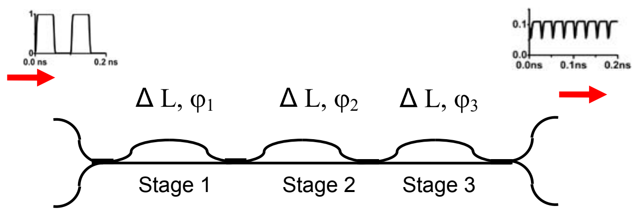

Figure 2. Three-stage LF-MZM for generation of optical signal at 40 GHz.

where i=0, 1, 2, for generation of 40 GHz pulse train were reported earlier in Ref. [8]. Compared to a one- or a two-stage device, this configuration provides better suppression of the carrier and other modes. LF-MZI performs both amplitude and phase filtering. The length difference ΔL of two arms in the MZI is determined by the desired free spectral range (FSR) of the output of the LF-MZI and is 5 mm for 40 GHz. This small difference in length of the LF-MZI may be realized in a PLC [8], where the MZI are implemented using Ge-doped silica-on-silicon waveguides with the multimode interference (MMI) couplers. Similar devices have been fabricated recently for pulse rate multiplication from 10 GHz to 40 GHz [9].

We analyzed the proposed scheme using OptiSystem software. The MZM-1 was driven by a 10 GHz signal comprising rectangular pulses with exponential rise and fall times of 5 picoseconds and calculated using an analytical model. Each stage in the LF-MZI had a coupler and one of the arms with a time delay of 0.025 ns and a corresponding phase shift φ_i. Although different optimal coupler split ratios were suggested in Ref. [8], we fixed them at 3 dB because this would simplify fabrication of the device [9]. Losses on coupling of the light to and from the device, and losses in the waveguide (~ 0.8 dB/cm, [9]) were ignored in the calculations.

The simulated optical spectra of the input and output of the LF-MZI is shown in Fig. 3 (a) and Fig. 3 (b). The output of only one arm of the LF-MZI is used for further transmission. The LF-MZI produces the spectrum with the FSR of 40 GHz and optical carrier suppression of > 40 dB. The beat tones do not occur at f_o+20 GHz and f_o-20 GHz, as in a OCS scheme with D-LN-MZM [3], but at f_o-10 GHz and f_o+30 GHz, where f_o = 193.414 THz (1550 nm). The suppression of the side tones at f_o+30 GHz and f_o-50 GHz, relative to f_o-10 GHz, is ~10 dB and 16 dB, respectively. The third-order 40 GHz harmonics, f_o+70 GHz and f_o-90 GHz, are suppressed by 20 dB and 24 dB, respectively.

The generated by LF-MZI optical millimeter-wave is then amplified by an EDFA (Fig. 1). Then, the signal passes through MZM-2, modulated with the downstream PRBS data at 2.5 Gbit/s. The resulted optical spectrum is shown in Fig. 3 (c). The optical carrier at 1550 nm is suppressed by 35 dB and the mm-wave is generated at 40 GHz. The beat notes at f_o-50 GHz and f_o+30 GHz are suppressed by 15.4 dB and 10 dB, respectively.

We compared the performance of the new scheme to the generation of 40 GHz mm-wave signal with OCS technique, shown schematically in Fig. 4 [3]. In our simulations of this

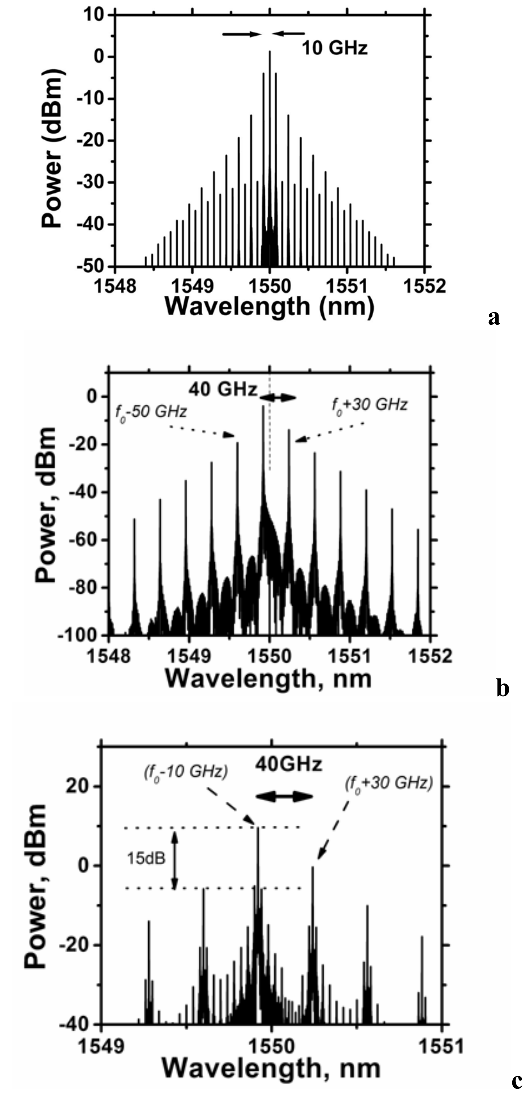

Figure 3. (a) Input and (b) output of the LF-MZI. (c) Output of the proposed central station.

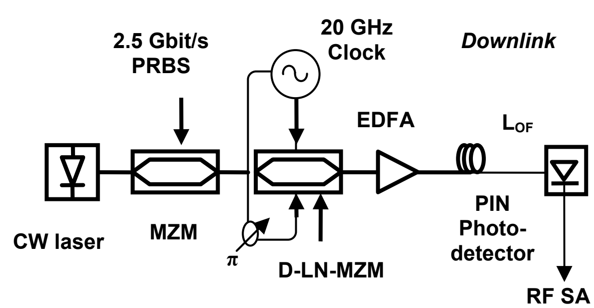

Figure 4. Simplified schematics of a ROF link with OCS using dual-arm $LiNbO_3$-MZM.

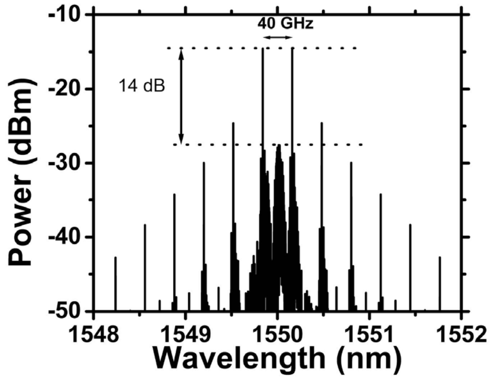

Figure 5. Optical spectrum simulated for the OCS scheme with D-LN-MZM.

link, the CW light wave is generated by a DFB laser (5mW output power at 1550 nm) and is modulated by 2.5 Gb/s pseudo-random-sequence signal using a MZM. Then, the optical signal passes through the D-LN-MZM, biased at Vπ and driven by two complimentary 20-GHz clocks [1-2]. The D-LN-MZM suppresses the optical carrier and produces two tones at f_o+20 GHz and f_o-20 GHz from the optical carrier f_o. Fig. 5 shows the simulated output of the D-LN-MZM. The result is similar to the one experimentally obtained in Ref. [3]. The carrier suppression is only 14 dB, whereas in Ref. [3] the measured carrier suppression was 25 dB.

III. DOWLINK TRANSMISSION IN DIFFERENT SCHEMES

We simulated transmission of the output of the central station with LF-MZI through the optical fiber in the downlink. Fig. 6 shows the simulated response of the photodiode when the length of the optical fiber link is L_{OF} = 0, 2, 20, and 50 km. The dispersion of the fiber was assumed to be 16.75ps/nm/km. Fig. 6 shows that the proposed method allows transmission of the millimeter-wave signal over 50 km, and even though the RF signal at 40 GHz weakens, it does not disappear as it was reported in [3] for most of the ROF schemes except of OCS.

When the MZM-1 is driven by a sinusoidal 10 GHz signal generator, the output of the LF-MZI has only two harmonics with optical power of higher than -50 dB: f_o-10 GHz (optical power P=-5 dB) and f_o+30 GHz (P=-38 dB). The optical carrier suppression in this case is 60 dB. The resulting RF tone has the power of -35 dB immediately after the central station, and -50 dB after 30 km of optical fiber.

For comparison, we calculated the transmission over 50 km for an OCS scheme with D-LN-MZM. Although the RF power at 40 GHz does not disappear, it becomes very weak (<5 dB suppression), which had been experimentally demonstrated in Ref. [3].

We designed another device based on a principle of the LF-MZI. The schematics of the device (LF-MZI-2) and its optical output, when optical input at 10 GHz is applied, are shown in Fig. 7. The LF-MZI-2 has five stages and the phase shifts of $\varphi_i = \{1.5; 1.5; 0.5; 0; 1.5\} \times \pi$, where i = 1…5. The

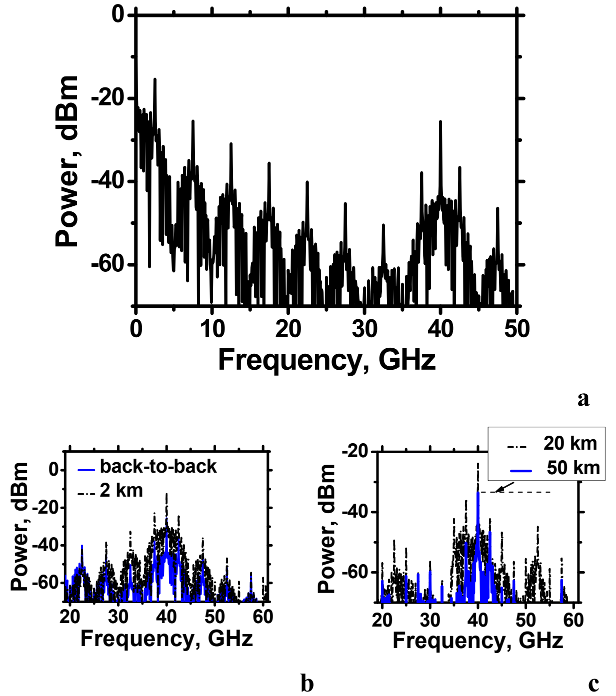

Figure 6. RF response of the photodiode in the proposed link: (a) back-to-back; (b) back-to-back and 2 km; and (c) 20 km and 50 km of the fiber link.

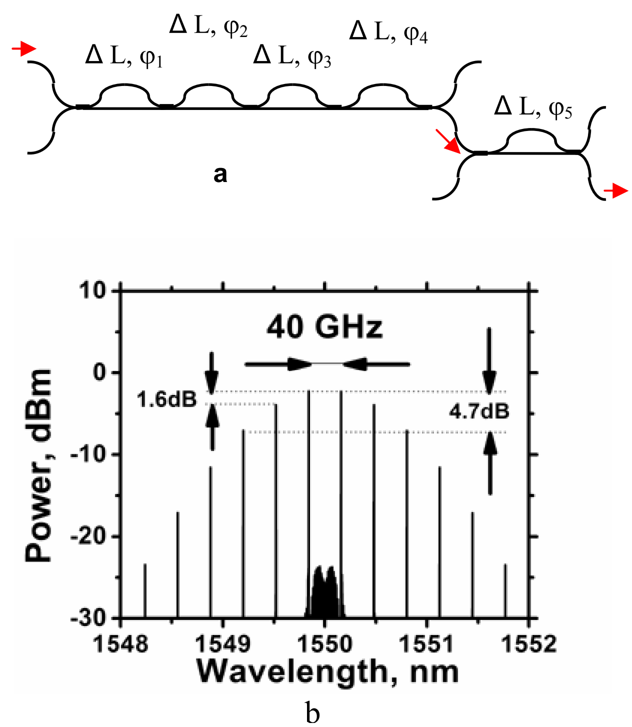

Figure 7. (a) Five-stage LF-MZI-2 for generation of optical signal at 40 GHz and (b) the optical output of the LF-MZI-2.

length difference between the MZI arms ΔL is 5 mm and corresponds to the time delay of 0.025 ns. The first four stages generate the beat signal at 20 GHz and the 5th stage up-converts the tone to 40 GHz. The output is amplified with an EDFA and passed through the MZM-2 driven by 2.5 Gb/s PRBS electrical signal. The RF signal at 40 GHz is very weak when transmitted over 1.5 km and practically disappears when transmitted over the 2 km link. However, the RF spectrum has a very clear peak at 120 GHz. This is explained by poor suppression of the first-order 40-GHz-sideband tones (1.6 dB) in the generated optical signal [4]. When the drive signal of the MZM-1 (Fig. 1) is sinusoidal, the output of the 5-stage LF-MZI-2 has only two tones at f_o+20 GHz and f_o-20 GHz with optical power of -25 dBm; optical carrier suppression is ~50 dB. The 40 GHz RF tone is well-pronounced, but looses power from -25 dBm to -45 dBm after transmission over 30 km of optical fiber.

Using the PLC technology, the LF-MZI may be designed and fabricated for pulse repetition rate multiplication from 10 GHz to 80 GHz and higher [8]. We believe that a properly designed LF-MZI PLC device can generate a stable high-frequency signal in ROF link at practically any frequency using 10 GHz signal generator and an inexpensive 10 GHz external MZM.

IV. Conclusion

A novel technique for generation of 40 GHz signal in a ROF link using an all-optical passive LF-MZI has been proposed and simulated. We have shown numerically, to our knowledge for the first time, that the new scheme can generate and transmit a 40 GHz signal with a MZM electrically modulated at only 10 GHz, which dismisses the necessity of a high-frequency (≥20 GHz) electrical signal generator and a D-LN-MZM in the ROF link. The transmission of the signal in the downlink has shown to be attainable even over 50 km of the optical fiber.

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