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Direct UV Written Michelson Interferometer for RZ Signal Generation Using Phase-to-Intensity Modulation Conversion

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***Abstract*—An integrated Michelson delay interferometer structure making use of waveguide gratings as reflective elements is proposed and fabricated by direct ultraviolet writing. Successful return-to-zero alternate-mark-inversion signal generation using phase-to-intensity modulation conversion is demonstrated up to 40 Gb/s using the device. Compared to other implementations, the device is compact, inherently stable, and allows for easy customization of the pulsewidth by proper positioning of the gratings on a single coupler structure.**

***Index Terms*—Delay interferometer (DI), direct ultraviolet (UV) writing, integrated optics, return-to-zero (RZ) generation.**

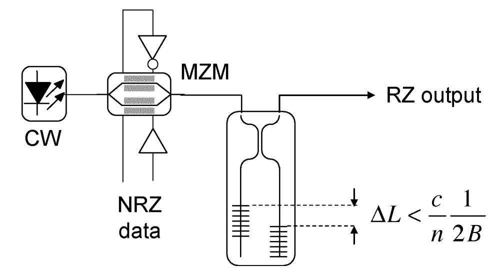

Fig. 1. Principle of operation of the RZ transmitter and structure of the proposed Michelson grating DI.

I. Introduction

Direct ultraviolet (UV) writing is a promising technique for the fabrication of optical waveguide components due to its simplicity compared to conventional clean room processing and its potential for large-scale production at a reduced cost [1]. Low-loss and low-birefringence waveguides have been fabricated, and a number of functionalities such as directional couplers, splitters [2], [3], and variable optical attenuators [4] have been demonstrated.

From the systems technology side, a tremendous research effort has been devoted over the past few years to the generation and investigation of the properties of novel modulation formats. Among those, the return-to-zero (RZ) alternate-mark-inversion (AMI) format has been shown to result in improved optical fiber nonlinearity tolerance over conventional ON–OFF keying at 40 Gb/s [5]. This format can be generated using phase modulation followed by a delay interferometer (DI) [6]–[9]. The method is cost effective since it enables optical RZ signal generation from conventional nonreturn-to-zero (NRZ) electronics and only requires a single phase or dual-drive Mach–Zehnder modulator (MZM). It is also flexible since the pulsewidth can be tailored by the choice of a proper delay. Planar lightwave circuit DIs based on the Mach–Zehnder structure are inherently stable and compact devices suitable for practical implementation in transmitter modules. However, generation of RZ pulses with a sufficiently high extinction ratio is only feasible at the price of a precise control of the coupling ratio of two 3-dB couplers, which might limit the fabrication yield of such devices. Furthermore, a totally new device design is required for each targeted pulsewidth, corresponding to a given delay, when such a Mach–Zehnder structure is used.

In this letter, we demonstrate a DI structure based on a direct UV written Michelson interferometer where the reflective elements are realized by waveguide gratings. The structure is simple since it consists of a single 3-dB coupler with waveguide gratings written in each arm. It is furthermore compact and allows for easy customization of the pulsewidth by simply adjusting the position of the gratings in the arms of a single coupler structure. Using the fabricated device, we demonstrate successful RZ-AMI signal generation at up to 40 Gb/s.

II. Principle of Operation

The structure of the RZ transmitter (shown in Fig. 1) is similar to the one proposed in [9]. An MZM driven in push–pull mode by differentially encoded NRZ data and inverted data at a bit rate B is used to generate phase modulation with instantaneous π phase shifts. A DI with delay smaller than the bit slot duration $1/B$ converts the phase modulation to intensity modulation and generates an RZ signal whose pulse full-width at half-maximum (FWHM) depends on the value of the delay and the modulation rise time [9]. Fig. 2 shows the calculated RZ pulsewidth as a function of the interferometer delay for different values of the NRZ electrical signal rise time. Our calculations

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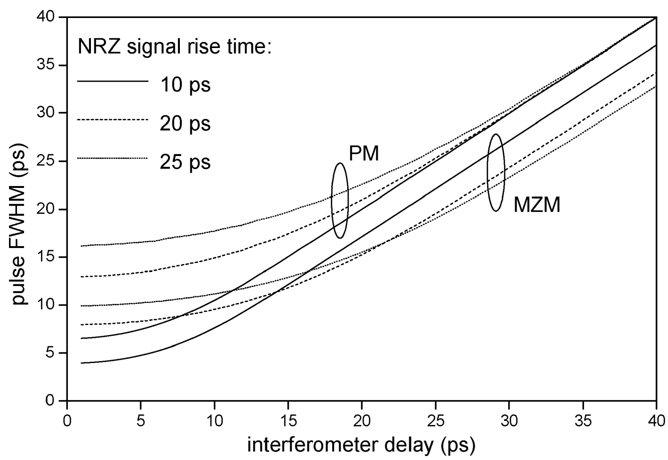

Fig. 2. Calculated pulse FWHM as a function of interferometer delay for different values of the NRZ signal rise-time for phase modulated signal generation using a phase modulator (PM) or an MZM.

confirm previous observations in [6] and [9], especially the different dependence of the pulsewidth on the delay depending on whether phase modulation is achieved in a phase modulator or a Mach–Zehnder intensity modulator biased at a null transmission point and driven between two consecutive maxima of its power transfer function. Fig. 2 allows the determination of the delay required to achieve a given pulsewidth, hence, the physical length difference between the interferometer arms, depending on the phase modulated signal generation method.

Our DI structure consists of a Michelson interferometer made from a coupler and two waveguides, all UV written, where reflective elements are implemented as intracore Bragg gratings. The delay is set by the path length difference accumulated for forward and backward propagation after reflection by the gratings, improving the compactness of the device compared to a conventional Mach–Zehnder structure. The influence of residual birefringence in the waveguides and grating is reduced as the device is implemented at the transmitter side, where polarization-maintaining connections would be used. Furthermore, compared to the Mach–Zehnder DI structures used until now, a single coupler is required, hence resulting in a better fabrication yield for devices achieving a required extinction ratio. As the same coupler is used for splitting and combining the incoming phase modulated signal, the extinction ratio does not depend on the coupling ratio, but only on the relative reflectivities of the two waveguide gratings. Finally, the same basic coupler structure can be used to realize a variety of RZ signal pulsewidths since the delay simply depends on the relative position of the two waveguide gratings in each arm of the coupler. However, unlike Mach–Zehnder DIs that can easily be tuned to different channel wavelengths due to the periodicity of their transfer functions, the limited bandwidth of the reflectors in our proposed structure requires customization of the device for a given channel or channel range. Note that Fig. 2 had assumed wavelength-independent attenuation for the two paths constituting the DI. This is typically the case for a Mach–Zehnder DI structure, but might need to be corrected for our proposed Michelson structure in case the bandwidth of the gratings becomes comparable to the spectral width of the phase modulated signal.

III. Device Fabrication and Properties

The Michelson interferometer was UV written by scanning a photosensitive sample fabricated by plasma-enhanced chemical vapor deposition under a focused UV beam [10]. The sample consisted of a silica-on-silicon structure containing Ge and B in the 5.5-μm-thick waveguide core layer [3] that had been deuterium loaded in order to increase its photosensitivity. The coupler was written with a UV beam (width: 3 μm at $1/e^2$) at 257 nm from a frequency doubled argon–ion laser. The incident UV power was 45 mW and the applied scan speed was 200 μm/s, resulting in 6.2-μm-wide waveguides with an index step of 0.006. One side of the coupler contained 2-cm-long waveguides spaced 250 μm apart to accommodate the Bragg gratings, giving a total component length of 3 cm. The measured insertion loss of a straight reference waveguide was 0.65 dB with a polarization-dependent loss of 0.25 dB. The waveguide center-to-center spacing in the central coupling region was 13 μm. The coupler excess loss was 0.2 dB and the coupling ratio was 0.8. As mentioned previously, this value does not impact the extinction ratio of the pulses but only affects the transmitted power. The coupling loss to standard single-mode fiber was less than 0.2 dB per facet, leading to a fiber-to-fiber loss of about 9 dB. A significant advantage of using the direct UV writing technique is that the same setup used for waveguide fabrication can be used for grating fabrication. To do this, the incident beam diameter was increased to 70 μm and a phase mask [11] was placed in direct contact with the sample. By appropriately scanning the sample, the location and extent of the gratings can be precisely controlled. In this way, 4-mm-long uniform gratings were written into each coupler arm with a relative displacement of 2.406 mm, so that a delay of 23 ps is achieved. The gratings had an attenuation in the stopband in transmission of 45 and 46 dB and a bandwidth of 80 GHz. Furthermore, the polarization-dependent wavelength shift of the interferometer transfer function was measured to be 0.02 nm.

IV. RZ Signal Generation

The performance of the fabricated device was evaluated at 10, 20, 30, and 40 Gb/s. The experimental setup is similar to the one represented in Fig. 1. As a pseudorandom binary sequence (PRBS) was used, no differential encoding of the data was performed prior to phase modulation. After RZ signal generation in the Michelson DI, the signal was preamplified by an erbium-doped fiber amplifier and detected in a photodiode with 50-GHz bandwidth. The same receiver configuration was used independently of the bit rate. In practice, phase tuning of the interferometer can be achieved using a heating element. In the present demonstration, the tunability of the laser source was exploited instead. Successful RZ signal generation was achieved at the output of the DI up to 40 Gb/s, as can be observed from the eye diagrams represented in Fig. 3. As expected, the duty cycle ratio of the generated RZ signal increases with increasing bit rates. Some pulse distortion begins to appear at 40 Gb/s, due to a slightly nonoptimal delay. The spectra recorded in a 0.01-nm resolution bandwidth at the output of the DI are shown in Fig. 4 in the case of 20- and 40-Gb/s operation, together with the measured relative transmission of one of the gratings.

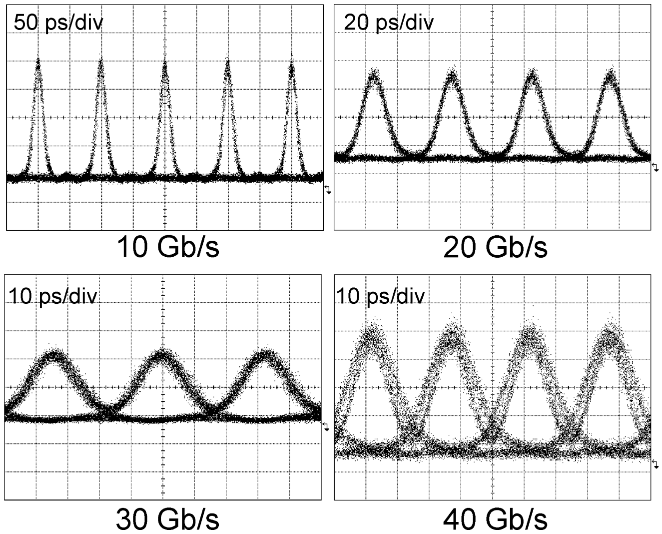

Fig. 3. Eye diagrams of the RZ signal at the DI output for 10-, 20-, 30-, and 40-Gb/s operation.

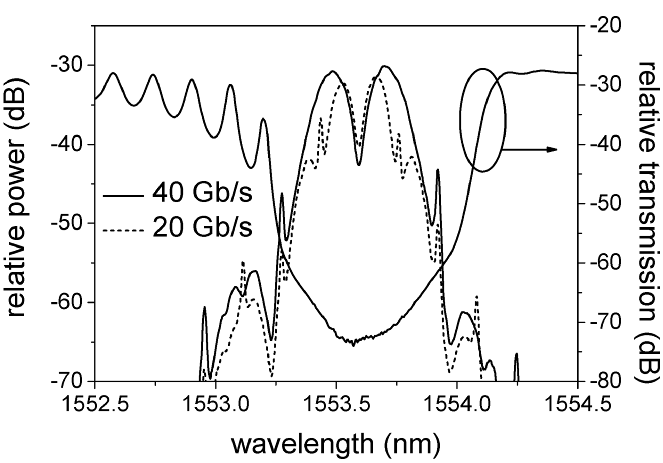

Fig. 4. Spectra of the RZ signals generated at the output of the Michelson DI at 20 and 40 Gb/s. The transmittivity of one of the grating reflectors is also represented.

They exhibit typical features of the RZ-AMI modulation format, namely a notch induced by destructive interference at the carrier frequency. Bit-error-rate (BER) curves measured at the output of the DI are shown in Fig. 5. The PRBS pattern length was $2^{31} - 1$. Beyond the reduction of the bit rate and associated lower signal-to-noise ratio requirements, the reduction of the duty cycle at lower bit rates is believed to contribute to the observed improved BER performance.

V. Conclusion

A DI structure aimed at RZ signal generation using phase-to-intensity modulation conversion of an NRZ signal has been realized. The device uses a Michelson interferometer structure fabricated by direct UV writing with waveguide gratings as

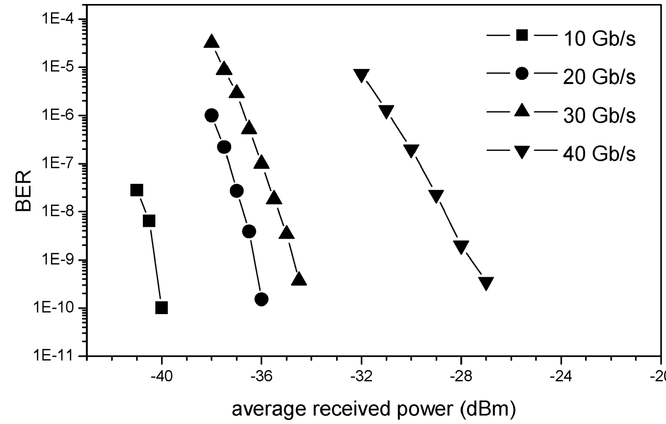

Fig. 5. BER curves for 10-, 20-, 30-, and 40-Gb/s operation.

reflective elements. Successful RZ signal generation has been verified up to 40 Gb/s. The device is compact, inherently stable, and allows for easy customization of the pulsewidth by proper positioning of the gratings on a single coupler structure. Consequently, the potential of the direct UV writing technique for fabrication of advanced components has been confirmed.

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