Analysis and Demonstration of Ultra-Broadband Mach-Zehnder Hybrid Polymer/Sol-Gel Waveguide Modulators

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Abstract: A bandwidth of the hybrid modulators is calculated numerically and analytically based on experimentally obtained device parameters, which is >130 GHz. The electro-optic response is reduced by < 2 dB at 67 GHz. The electrical transmission S_{21} is reduced by 5 dB at 110 GHz (upper limit) of a vector network analyzer, which also assured the bandwidth.

1. Introduction

The data center moves forward to an optical transmission speed of 100 Gbit/s, and aims to 400 Gbit/s in a few years based on an optical module (e.g. optical transceiver). Multi-channel approach is required to catch up with the speed using multiple semiconductor lasers, electro-optic (EO) modulators, and optical detectors. Reducing the number of these optical devices enables to reduce the cost of the optical modules. For the reason, the bandwidth of the EO modulator of >100 GHz will be the most advantageous and important to reduce the number of the optical devices. EO modulators directly driven by CMOS in large-scale integration circuit will be suitable devices in the test equipments [1], in which the high-speed electronics in the test equipments are driven by voltage amplitude of 1-2 V_{pp}. When an EO polymer is employed in the modulators, the bandwidth of the MZ optical modulators can be extended with reducing half-wave voltage (V_π). A hybrid EO polymer/sol-gel silica MZ waveguide modulator [2] showed the lowest V_π of 0.65 V (in-device EO coefficient of 142 pm/V) for 2.4-cm-long dual derived electrode [3] and an optical propagation loss of 5 dB/cm, which corresponds to $V_\pi L$ of 1.56 Vcm and $V_\pi Loss$ of 7.8 VdB. Enami et al. also first demonstrated EO polymer/TiO_2 vertically confined slot waveguide modulators on the sol-gel silica cladding to reduce the electrode distance in 2012 [4], and showed the EO coefficient of >200 pm/V [5]. The hybrid EO polymer/sol-gel silica (or TiO_2 slot waveguide) modulator is one of the best modulators that would have ultra-broadband modulation [6, 7] with maintaining high-quality of EO modulation (index change is linear to voltage signal), lower optical loss, and lower V_π. In the hybrid EO polymer/sol-gel waveguide modulators, all-dielectric material has lower conductivity (enables wider bandwidth) than that of any other semiconductor modulators and higher poling efficiency of the EO polymer. Here, we analyze and demonstrate the over 110 GHz ultra-broadband MZ modulator based on hybrid EO polymer/sol-gel waveguide.

2. Ultra-high-speed electro-optic modulators

Hybrid EO polymer/sol-gel silica waveguide modulators have single or dual RF traveling-wave microstrip line on the top to cover the MZ waveguide arms. An Au lower ground electrode underneath the sol-gel silica cladding was connected with Au electrode pads fabricated on the modulator surface using an Au via pillars. Both Au top RF traveling-wave electrode and Au electrode pads (via the lower ground electrode) were set in a coplanar position to be connected with high frequency probes or connectors. The electrical signal from the coplanar electrode was transmitted through a microstrip line without any significant conversion loss. An output of RF traveling wave was also designed and set in the coplanar position to be terminated with a impedance matched terminator of 50 Ω. The RF transmission parameter S_{21} was measured from 10 MHz to 110 GHz.

2.1 Electrical response

In the calculation of the frequency response of the electrical transmission S_{21} parameter, the dielectric constant, conductivity and the thickness of the materials in the modulators were accurately measured by our technique. The S_{21} for the modulator (5-mm-long electrode) was calculated using experimentally obtained device parameters. The calculation showed the bandwidth of 130 GHz for 6 dB drop of the transmission parameter S_{21} that corresponds to the bandwidth of the EO response for 3dB drop when the phase velocity is well matched in the frequency range.

The electrical transmission parameter S_{21} and reflection parameter S_{11} for the milliwave in the RF traveling electrode was measured using a 110 GHz network analyzer, which was fitted with numerically calculated results using high frequency simulator HFSS. At 50 GHz of the network analyzer, the electrical transmission parameter S_{21} was reduced to -2.6 dB for the modulator (5-mm-long electrode). The experimentally measured electrical transmission parameter S_{21} was reduced to -4.6 dB for the modulator (5-mm-long electrode) at the network analyzer limit of 110 GHz. The measured result assured that the bandwidth of 130 GHz for a 6 dB decrease in the transmission parameter S_{21}, which corresponded to the bandwidth of the EO response for a 3 dB decrease. The electrical reflection S_{11} parameter was also measured from 10 MHz to 110GHz, and the parameter S_{11} was less than -10 dB. The experimental result indicates that the input impedance of 50 Ω at the input port was widely matched for impedance up to 110 GHz by our modulator design.

2.2 Electro-optic response

The response of the EO modulation with respect to milliwave frequency depends on the transmission loss of the milliwave in the RF traveling electrode, impedance mismatch, and phase velocity mismatch between the optical wave and milliwave. The simulation involves the transmission loss of the milliwave and impedance mismatch for the actually fabricated EO modulators with 5-mm and 10-mm long electrodes. When the impedance matching condition was optimized well, the transmission loss of the milliwave was obtained. In this case, the response *M (f)* of the EO modulation is also expressed as

$$M(f) = e^{-\alpha L/2}\left|\frac{\sinh^2(\alpha L/2) + \sin^2(\xi L/2)}{(\alpha L/2)^2 + (\xi L/2)^2}\right| \tag{1}$$

$$\xi = 2\pi f\left|n_{mw} - n_{opt}\right|/c \tag{2}$$

where α, L, and c are the electrical transmission loss, the electrode length, and speed of light in vacuum, respectively[7].

The EO response for a 5- and 10-mm-long single-driven modulators was measured experimentally using the vector network analyzer with a calibrated OE (opto-electronic) module, as shown in Fig. 1.

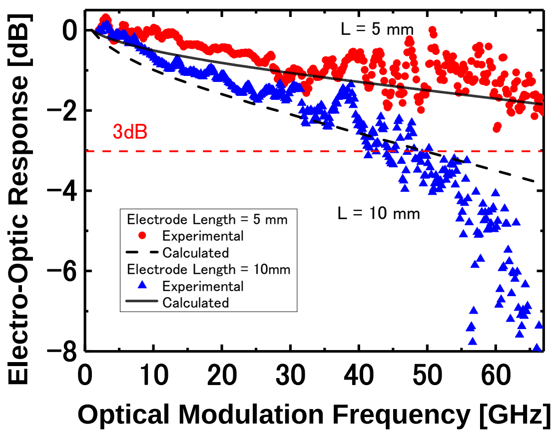

Fig. 1 Frequency response of EO modulation for the hybrid EO polymer/sol-gel silica waveguide modulator. The red circles and blue triangles indicate the experimentally obtained EO response for the modulator of 5- and 10-mm-long electrodes, respectively.

The EO response was reduced by < 2 dB at 67 GHz for the modulator (5-mm-long electrode), which matched to the calculated results. When we examined the EO response of the modulator with 10-mm-long electrode, the bandwidth of the EO response was ~45 GHz, which was also similar to our calculated bandwidth of 48 GHz. The measured EO response of the modulators (10- and 5-mm-long electrode) was matched well with theoretically obtained one up to 50 GHz. The position of the RF connection is also optimized for minimum reduction of the electrical transmission S_{21} and lower electrical reduction S_{11} using HFSS.

2.3 Large signal transmission and device performances

A large signal transmission (NRZ) at a bit error rate of 56 Gbps (upper limit of our equipments) for a driving voltage of 1.5 V_{pp} was measured for the optical modulators using a programmable pulse pattern generator and a sampling oscilloscope. The clear open of the eye diagram of >200 Gbps can be obtained since the 3-dB drop-bandwidth of the modulators is much wider (e.g. 130 GHz). In-device EO coefficient was measured to be 160 – 200 pm/V from the experimentally obtained $V_\pi L$ of 1.8 Vcm (dual driving), d of 13.3 μm. When the d is decreased down to 9 μm, which does not experimentally suffer additional optical loss from both top and lower electrodes due to the optical absorption, $V_\pi L$ of 1.2 Vcm will be obtained.

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3. References

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