Method for Characterization of Electro-Optic Phase Modulators

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Abstract — We present a method to characterize the efficiency and optical loss of an electro-optic phase modulator (EOPM). The efficiency and loss are not constant but change with wavelength and bias voltage, although in literature often only a single value is given. Our characterization method better represents the performance and provides valuable insight into the device operation. No integrated passive structures are required, making it a straightforward and widely applicable characterization method. We applied the method to EOPMs of different lengths. The results show the trade-off between efficiency and optical loss. They are used to find the optimum operating point and to design and optimize the EOPM layer stack.

Index Terms — Characterization, electro-optic modulators, Fabry-Pérot interferometers, optical losses, phase shifting.

Introduction

Phase modulators are one of the key building blocks needed in an optical communication system. The ever-increasing demand for data communication puts stringent requirements on these building blocks. A good characterization method is required to assess the performance of a phase modulator. This will enable the comparison of different designs and help to identify the various trade-offs.

Two metrics often used for phase modulators are $V_\pi L$, the voltage and length needed for a 180° phase shift of the optical signal; and insertion loss (IL), the amount of light lost after the optical signal passed through the phase modulator. However, these metrics change substantially with wavelength and bias voltage. We present a characterization method that better maps this dynamic behavior, by determining both the efficiency $V_\pi L(\lambda, V_{\text{bias}})$, and optical loss $\alpha(\lambda, V_{\text{bias}})$, as a function of wavelength and bias voltage.

An interferometric method is needed to measure phase shift and optical losses accurately. The presented characterization is based on the Fabry-Pérot method [1, 2], often used to measure optical losses in passive waveguides. Only a certain length of phase modulator with cleaved facets is needed. This method is more direct than characterizing the phase modulator inside a Mach-Zehnder interferometer (MZI) structure. The MZI method will be limited by the imbalance and operating bandwidth of the spitters/combiners (e.g. multi-mode interference (MMI) couplers). Also, good electrical isolation is needed. The Fabry-Pérot method does not have these limitations.

In the next section, the theory and the general methodology are presented. This is followed by the experimental results of the characterization technique applied to an InP-based modulator.

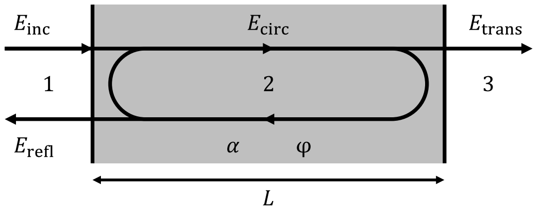

Fig. 1. Schematic representation of an EOPM of length L forming a Fabry-Pérot cavity. The incident, circulating, reflected, and transmitted electric fields are indicated.

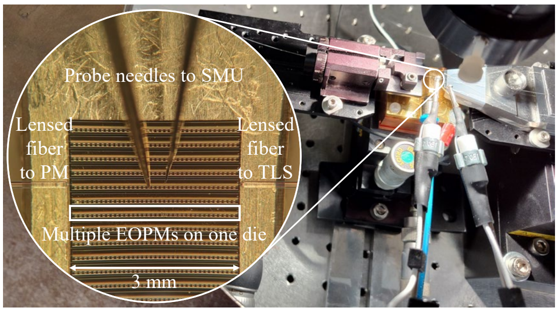

Fig. 2. Photograph of the measurement setup including a view through the microscope.

Methodology

This section will explain how the optical loss can be determined from the measured fringe pattern from the Fabry-Pérot setup. Furthermore, the relation between the induced phase shift by the EOPM and the fringe pattern will be given.

The phase modulator to be characterized is cleaved at both sides. The cleaved facets act as mirrors such that a Fabry-Pérot cavity is formed, schematically shown in Fig. 1. Making use of the infinite sum of the successive reflected and transmitted fields, the power transmission can be represented as

$$\frac{P_{\text{trans}}}{P_{\text{inc}}} = \left| \frac{t_{12} t_{23} e^{-\frac{1}{2}\alpha L} e^{-j\varphi}}{1 - r_{23} r_{21} e^{-\alpha L} e^{-j2\varphi}} \right|^2 = \frac{t_{12}^2 t_{23}^2 e^{-\alpha L}}{(1 - r_{23} r_{21} e^{-\alpha L})^2 + 4 r_{23} r_{21} e^{-\alpha L} \sin^2 \varphi} \tag{1}$$

with α the power attenuation factor (so single-pass amplitude attenuation equals $e^{-\frac{1}{2}\alpha L}$), φ the accumulated phase over a single pass of length L, t_{12}, t_{23}, r_{23}, and r_{21} the amplitude transmission and reflection coefficients for the facets (the subscript indicating the regions as shown in Fig. 1). The transmitted power is maximum for $\varphi = m\pi$ and minimum for $\varphi = m\pi + \frac{\pi}{2}$, with m an integer. By measuring the fringe pattern of the transmitted power the optical losses in the cavity can be calculated from the maxima and minima using

$$\alpha = -\frac{1}{L} \ln \left(\frac{1}{R} \frac{\sqrt{C} - 1}{\sqrt{C} + 1} \right) \tag{2}$$

with $C = P_{\max}/P_{\min}$ the contrast, $R = r_{23} r_{21}$ the power reflectivity of the facets (assuming both facets are identical) and L the length of the EOPM.

In our characterization method, this is done using a sweep in wavelength for a few discrete settings for V_{bias}. The losses can be calculated for each peak and valley pair for the entire wavelength sweep range. This will result in a loss versus wavelength curve for each set V_{bias}. It should be noted that the length L and the facet reflectivity R should be known to calculate the losses from the measurements. The length is easy to obtain but the reflectivity often needs to be simulated.

For determining the efficiency of the EOPM the same structure in the same experimental setup is used. Now, a sweep for V_{bias} is done for a few discrete wavelengths. Because the entire cavity is formed by the EOPM, the accumulated phase will depend on the applied voltage V_{bias}. As stated before, the transmitted power is maximum for $\varphi(V_{\text{bias}}) = m\pi$ and minimum for $\varphi(V_{\text{bias}}) = m\pi + \frac{\pi}{2}$. Thus, the voltage needed to go from one peak (valley) to the next peak (valley) in the measured fringe pattern ($V_{2\pi}$ of the round-trip) gives V_π of the EOPM around that particular V_{bias}. By considering multiple peaks and valleys, this will result in an efficiency versus voltage curve for each set wavelength.

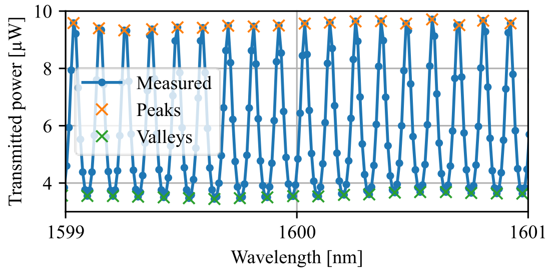

Fig. 3. Measurement data from a wavelength sweep for a 3 mm device with the bias voltage set to 0 V. Only a small part of the wavelength range is shown to be able to see the fringes.

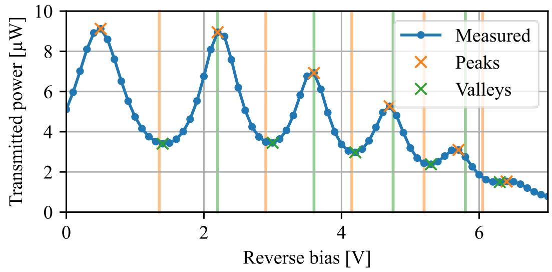

Fig. 4. Measurement data from a voltage sweep for a 3 mm device with the wavelength set to 1595 nm. The centers between peaks/valleys are indicated with vertical lines (differences are mapped there).

Results

The presented measurement technique was applied to fabricated InP-based modulators with multiple quantum wells (MQWs). In total, 12 devices were measured, all with the same layer stack and waveguide design. The modulators were cleaved to a length of 1 mm, 2 mm, or 3 mm; four different devices were measured for each length.

The dies with the different devices were placed on a chuck without temperature control. Light from a tunable laser source (TLS) (Agilent 81600B) was coupled to the device under test (DUT) with a lensed single-mode fiber. The polarization was aligned to the TE mode of the chip using a fiber rotator. The output power of the TLS was set to -10 dBm. The transmitted power was measured with a power meter (PM) (Agilent 81636B), using another lensed single-mode fiber. The bias voltage was applied with a source measure unit (SMU) (Keithley 2401), using two DC probe needles. The two fibers need to be accurately aligned to the DUT, which was done with two nanopositioning stages. During alignment, the TLS was exchanged for a broadband light source (Thorlabs S5FC1005P). This ensured proper alignment to the fundamental waveguide mode. A photograph of the experimental setup is shown in Fig. 2.

To determine the optical loss $\alpha(\lambda, V_{\text{bias}})$ of the DUT, the wavelength was swept from 1450 nm to 1640 nm in steps of 0.01 nm for nine different reverse bias voltages between 0 V and 10 V. This small step size is needed to acquire enough data points per fringe (one fringe is on the order of 0.1 nm for a 3 mm device). Part of one of these measurement sweeps is shown in Fig. 3. The data was processed in Python as follows. For each measured power versus wavelength curve, the peaks and valleys were found (on the order of 10^3 peaks and valleys, depending on L and V_{bias}). For a sample wavelength of 1520 nm to 1640 nm in steps of 0.02 nm, the contrast C was calculated using the nearest peak and valley. For each sample wavelength the optical attenuation was calculated using (2), which was then converted from m^{-1} to dB/cm and smoothened with a Savitzky-Golay filter. This resulted in the loss $\alpha(\lambda, V_{\text{bias}})$ of the modulator as shown in Fig. 5.

The value used for the power reflectivity R of the fundamental mode on the facet is 40%. This was simulated using an internal program called mirf (which decomposes the field into a plane wave spectrum) and confirmed by finite-difference time-domain (FDTD) simulations (using Ansys Lumerical). Note that R should not be calculated by simply using the Fresnel equation for normal incidence (which would give 29%, using the effective index of the fundamental mode).

To determine the efficiency $V_\pi L(\lambda, V_{\text{bias}})$ of the DUT, the bias voltage was swept for a reverse bias from 0 V to 10 V in steps of 0.1 V for nine different wavelengths between 1520 nm and 1640 nm. Part of one of these measurement sweeps is shown in Fig. 4.

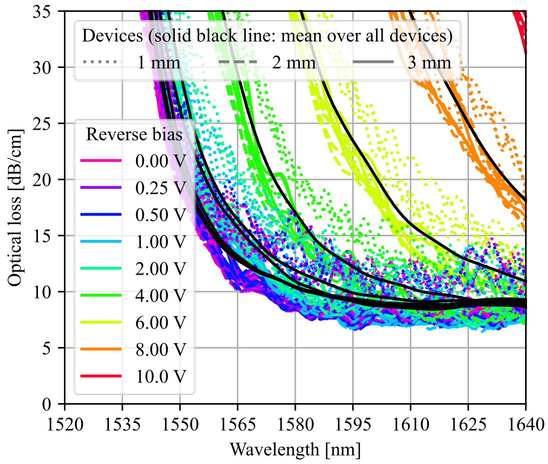

Fig. 5. Processed results on the optical loss of the InP-based modulator design. For this purpose $12 \cdot 9 \cdot 19001 = 2052108$ experimental data points were collected. The losses could be determined up to ~40 dB/cm before the losses became too high to observe clear fringes. The four devices for each length are plotted with the same line style.

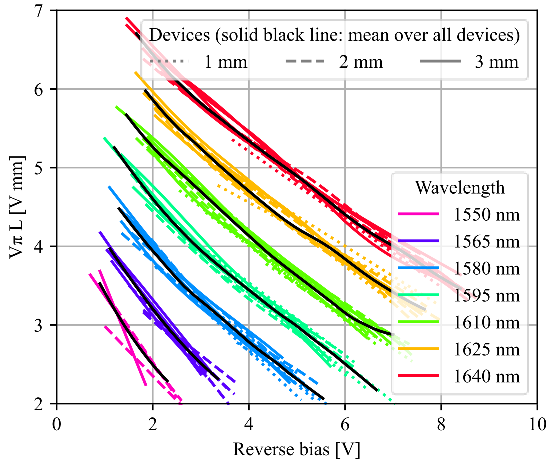

Fig. 6. Processed results on the efficiency of the InP-based modulator design. For this purpose $12 \cdot 9 \cdot 101 = 10908$ experimental data points were collected. For the measurements at 1520 nm and 1535 nm the losses were too high to observe clear fringes. The four devices for each length are plotted with the same line style.

The data was processed in Python as follows. For each measured power versus voltage curve, the peaks and valleys were found. The voltage difference between each pair of consecutive peaks (valleys) was calculated. This value for V_π was saved for V_{bias} in the center of the two peaks (valleys), leading to a number of data points for $V_\pi(V_{\text{bias}})$. A linear fit (3 or 4 points) or a smoothing spline (5 or more points) was applied, or the data was discarded (0 to 2 points). The resulting V_π versus V_{bias} curves were multiplied with the device length, to yield the efficiency $V_\pi L(\lambda, V_{\text{bias}})$ of the modulator as shown in Fig. 6. Together Fig. 5 and Fig. 6 give a good insight into the dynamics of the optical losses and the efficiency of the EOPM design. It can be used to find a suitable operating point within the trade-off between loss and efficiency. For example, estimating from Fig. 5 and Fig. 6, to achieve an efficiency of 4 V mm, at an operating wavelength of 1610 nm, the reverse bias voltage should be at least 4 V. This would imply an optical loss of at least ~11 dB/cm. The results of the devices of different lengths agree well with each other, showing the independence of the characterization method on the length L of the DUT. However, the loss measurement appears less accurate for the devices of 1 mm. Also, the remaining modulation on the curves shown in Fig. 5 is something that could be further investigated.

Conclusion and Outlook

With the presented characterization method the efficiency $V_\pi L(\lambda, V_{\text{bias}})$ and optical loss $\alpha(\lambda, V_{\text{bias}})$ of an EOPM can be obtained as a function of wavelength and bias voltage. The characterization technique was applied to an InP-based modulator showing clearly the trends of these two key performance metrics. This insight is now used to optimize the layer stack and the presented method will be used to characterize future EOPM designs.

References

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