Microwave model for optimizing electro-optical modulation response of the Mach-Zehnder modulator

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ABSTRACT

A model is created to study the role of impedance matching in indium phosphide modulators. The frequency-dependent characteristic impedance and propagation constant of the electrical transmission line structure is calculated from the cross-section of the phase modulator, electrode geometry, and p-i-n junction. The impedance and propagation constant are used in combination with a closed-form approximation for the traveling wave electrode and electrical circuit to create the non-iterative compact model. It yields good agreement with the experiment in a 50 Ohm measurement environment and the effect of changing source and termination impedance has been modeled. The 3dB optical modulation bandwidth is predicted to increase from 30GHz to 60GHz with optimized impedance matching and the associated suppression of electrical reflections.

Keywords: High-speed modulator, Mach-Zehnder, traveling wave electrode, termination impedance

1. INTRODUCTION

The growth in bandwidth-demanding applications such as cloud computing and online information exchange requires high-speed, fiber-optic communications. Mach-Zehnder modulators (MZMs) have been demonstrated with modulation speeds of order 100 GBd [2], enabling high data rates with high-order modulation formats [3].

To properly design such modulators for high-speed applications, accurate modeling and simulation tools are needed that capture both the microwave signal propagation and the electro-optic interactions. Modeling approaches exist that are based on large iterative EM simulation [4] or the Method of Lines [5], which can become very complex in nature. In this work, we use a simple analytical model that requires the geometrical and physical parameters of the modulator and its frequency-dependent, characteristic impedance and propagation constant. The former are direct design input variables and the latter two are obtained through fast 3D EM simulation, e.g. with CST Microwave Studio [6]. We show in this paper that our simple model can yield accurate predictions. The dimensions of a fabricated device as seen in Fig. 1.c) act as the reference design for our model. We validate our approach by comparing the simulation results with experimental measurements of the reference design and investigate the effect of the source and termination matching on the modulator performance.

2. MZM MODEL

The reference modulator used for validating the model is a hybrid co-planar waveguide (HCPW) MZM design, where the electrodes are in two different planes above and below the p-i-n junction. The MZM is connected to the source and termination with electrical coplanar waveguide probes. Figure 1.a is the schematic of the single drive HCPW-MZM. A source is applied to the central (signal) electrode with respect to the two ground lines of the HCPW structure. Z_s is the source impedance of the electrical driver, and Z_t is the termination impedance at the output of the MZM traveling wave electrode. The reference design has the cross-sectional parameters shown in Table 1 and Figure 1b. The model does not include bond-pads and tapers for electronic connections because it is intended to explore the ultimate technology limits of the inherent modulator itself. The model input consists only of parameters that can be directly controlled and specified in fabrication.

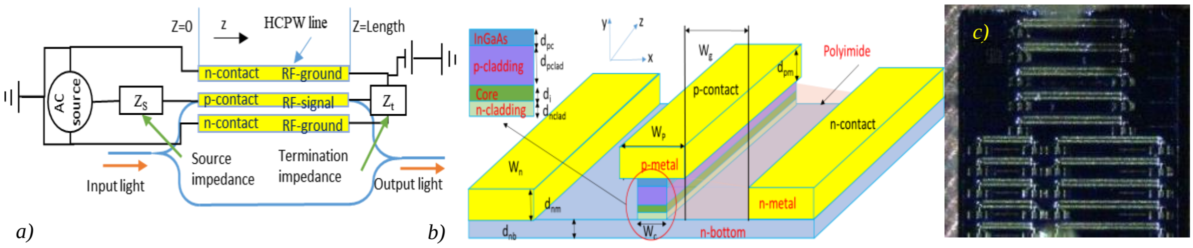

Figure 1. a) Single drive schematic b) the elevated view cross-section and c) the fabricated reference HCPW-MZM

The optical waveguide includes a p-i-n structure with an intrinsic core layer and p-cladding and n-cladding layers above and below. A highly doped InGaAs ternary-layer (p-contact) is between the p-metal and p-cladding to minimize the contact resistance. The signal p-metal line is located above the optical waveguide, and the two n-metal ground lines are offset from the waveguide on the n-bottom layer. The length of the reference design is 1mm, and the gap between ground and signal is 11μm.

TABLE 1. PARAMETERIZATION OF THE REFERENCE HCPW-MZM (DESIGN VALUES)

Layer	Doping (cm^{-3})	Thickness (μm)	Width (μm)	Resistivity (Ω.m)
n-metal		d_{mn}=2	w_n=20	ρ_{mn}= 2.5x10^{-8}
p-metal		d_{mp}=2	w_p=9	ρ_{mp}= 2.5x10^{-8}
p-contact	1x10^{19}	d_{pc}=0.28	w_c= 1.4	ρ_{cp}= 4.34x10^{-5}
p-cladding	1x10^{18}	d_{pclad}=1.35	w_c=1.4	ρ_{pclad}=10^{-3}
Intrinsic	n.i.d	d_i=0.21	w_c=1.4	Infinite
n-cladding	6x10^{16}	d_{i2}=0.31	w_c=1.4	ρ_{nclad}=6.097x10^{-5}
n-bottom	5x10^{17}	d_{nb}=1.5		ρ_{nb}= 3.62x10^{-5}

The AC-voltage source applied to the HCPW, a quasi-TEM transmission line, can be expressed as a superposition of forward and backward (reflected) waves at time t and distance z along with the modulator [1]:

$$V_m(z,t) = V^+ e^{j\omega\left(t-\frac{n_m z}{c_0}\right)-\alpha_m z} + V^- e^{j\omega\left(t+\frac{n_m z}{c_0}\right)+\alpha_m z} \quad (1)$$

where V^+ and $V^-$are complex constants that will be determined from the generator and load conditions [1]. In this work, we assume that the change of the optical refractive index and the associated change in the optical phase depends linearly on the modulating voltage. In the MZ interferometer, the output optical intensity follows a cosine dependence on the optical phase change. At quadrature bias and under small-signal approximation, the intensity variation is linearly proportional to the optical phase change. The small-signal normalized modulation index M(ω) can then be expressed in the form of the modulating phase change as:

$$M(\omega) = \left|\frac{\Delta\phi(\omega)}{\Delta\phi(0)}\right| = \frac{R_t+R_s}{R_t}\left|\frac{Z_{in}}{Z_{in}+Z_s}\right|\left|\frac{(Z_t+Z_m)F(u_+)+(Z_t-Z_m)F(u_-)}{(Z_t+Z_m)e^{\gamma_m L}-(Z_t-Z_m)e^{-\gamma_m L}}\right| \quad (2)$$

where $\Delta\phi(\omega)$ is cumulative phase modulation over the interaction length L, and

$$F(u) = \frac{1-exp(u)}{u}, \gamma_m = \alpha_m + j\frac{\omega n_m}{c_0}, u_\pm(\omega) = \pm\alpha_m L + j\frac{\omega}{c_0}(\pm n_m - n_0)L \quad (3)$$

$$Z_{in} = Z_0 \frac{Z_t + Z_m tanh(\gamma_m L)}{Z_m + Z_t tanh(\gamma_m L)} \quad (4)$$

$M(\omega)$is the frequency-dependent, small-signal normalized modulation index which includes walk-off for the difference in the microwave and optical propagation constants $\beta_e = \frac{n_m\omega}{c_0}$ and $\beta_0 = \frac{n_0\omega}{c_0}$. The optical refractive index n_o, of the reference design is 3.7 and c_0 is the speed of light in vacuum. The equation (2) also includes the effect of single back-reflections from the source impedance Z_s and the termination impedance, Z_t. R_t and R_s are the real part of termination and source impedances.

γ_m and Z_m are the frequency-dependent electrical complex propagation constant and the characteristic impedance of the HCPW-MZM, respectively, which are calculated by the CST-simulation tool using the cross-sectional data in Table 1. The solver divides the 3D-structure into tetrahedral meshes and calculates the electrical s-parameters of the entire structure. This simulation only needs to be performed once for a given cross-section and can be further used in the analytical model. The frequency response is assessed in terms of the electrical transmission along the transmission line from the source to termination, the characteristic impedance, and the modulation index $M(\omega)$.

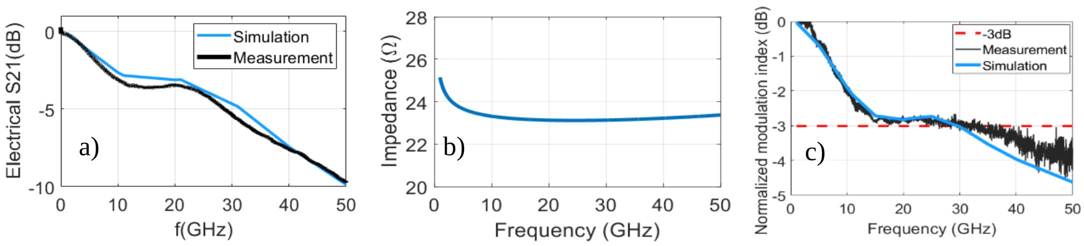

Figure 2. Frequency dependent response for the Mach-Zehnder a) comparing simulation and measurements for the electrical S_{21} of the microwave transmission line, b) the simulated characteristic impedance of the reference HCPW line and c) comparison between the simulated and measured electro-optic modulation response. Data shown for a 50 Ω source and termination.

The 3D-simulated electrical scattering parameters of the reference design are compared for modeled and measurement data for an experimental device in a 50 **Ω** measurement system. The measured and simulated electrical S_{21} transfer functions are presented with good agreement in figure 2.a. The simulated magnitude of the frequency-dependent characteristic impedance of the modulator is shown in figure 2.b. The characteristic impedance of the reference modulator design is between 23 to 25Ω in the simulated frequency range, indicating a significant mismatch between modulator, source, and termination. In figure 2.c, we compare the measured electro-optical-frequency response with the calculated modulation index $M(\omega)$ of the reference HCPW-MZM when both source and termination impedances are 50 Ω. This figure shows the agreement for measurement and calculation and a -3dB EO-bandwidth at 30GHz.We have developed a simple and accurate model that combines analytical expressions with line parameters obtained from 3D EM simulators, have shown that it can effectively predict device performance and have validated its output with experimental data.

3. CODESIGN FOR REFLECTION SUPPRESSION

The modulation bandwidth is believed to be compromised by electrical reflections from the impedance mismatch, and so a study has been performed with the model to evaluate the effect of source and termination impedance mismatch on the electro-optic modulation response. The electro-optic frequency response is calculated for impedances from 20 to 55 Ω for our reference modulator.

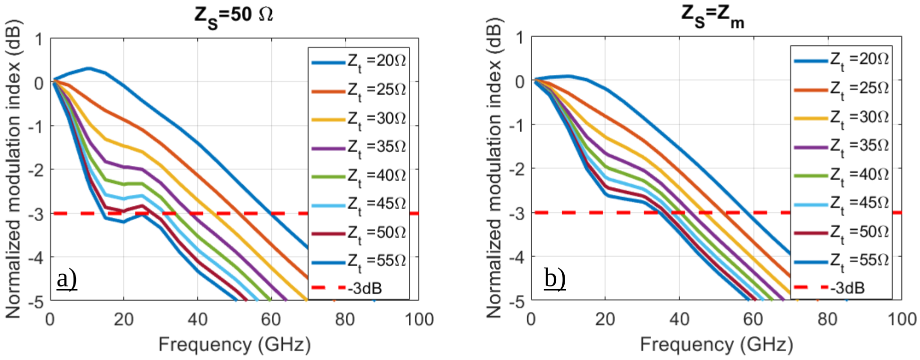

Figure 3. The role of impedance mismatch on the optical modulation bandwidth for a) A 50 Ω source impedance and varied termination impedance and b) A source impedance perfectly matched to the modulator characteristic impedance, with varied termination impedance. The modulator impedance is given in Fig 2b

Figure 3 shows the normalized modulation index $M(\omega)$ as a function of the termination impedance Z_t where a) $Z_S = 50\Omega$ and b) $Z_S = Z_m$. Fig. 3a shows that matching termination impedance (Z_t~25Ω) to the characteristic impedance of the HCPW-line, instead of having 50Ω termination, doubles the -3dB EO-bandwidth of the reference MZM. When we match the termination impedance (Z_t~25Ω), the effect of source impedance mismatch when comparing Fig. 3a) and b) is not significant. When the termination is not matched to the modulator impedance (Z_t=50Ω), the source impedance matching plays a role, increasing the 3dB bandwidth from 30 GHz to 38 GHz. Comparison of these two figures shows that the load impedance has a higher impact on the electro-optical bandwidth than the source impedance. Matching the termination side also enables a flatter modulation response. This motivates the use of lower than 50Ω terminations, and also the use of low impedance co-designed electrical drivers. Such an approach will, however, be highly sensitive to the interconnection between the electrical components and the Mach-Zehnder modulator, motivating the intimate integration of electronics and photonics.

4. CONCLUSIONS

A simple combined model for the electrical and electro-optical-frequency response of the HCPW-MZMs is presented with a good experimental agreement. We show that matching the termination and source impedances can increase the EO-bandwidth of the reference modulator from 30GHz to 60GHz. This research was carried out within the Dutch NWO HTSM Photronics project.

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