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Standing-Wave Enhanced Electroabsorption Modulator for 40-GHz Optical Pulse Generation

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***Abstract*—Compact 40-GHz optical pulse generators are crucial to the implementation of practical 160-Gb/s optical time-division-multiplexing systems with 40-Gb/s electrical time-division-multiplexing tributaries. In this letter, we report on a novel standing-wave enhanced mode of the electroabsorption modulator (EAM) which can improve the performance of a single EAM for 40-GHz pulse generation. Both experimental and theoretical results indicate that the distributed effect plays an important role in the high-frequency operation of the EAM and the length of the microwave termination line must be adjusted properly to maximize the performance.**

***Index Terms*—Electroabsorption, optical fiber communication, optical pulse generation, simulation, traveling-wave devices.**

I. Introduction

AS A RESULT of advances in high-speed electronics, future optical time-division-multiplexing (OTDM) systems over 160 Gb/s per wavelength may be constructed with 40-Gb/s electrical time-division-multiplexing (ETDM) tributaries to minimize the complexity of these systems. Several demonstrations were reported recently using electroabsorption modulators (EAMs) as key components both in the transmitter and the receiver design [1], [2]. The functionality of the EAM in these 160-Gb/s OTDM systems includes optical pulse generation, data encoding, optical demultiplexing and clock recovery. Except for data encoding, which is broad band in nature, all these functions require 40-GHz single frequency operation. In particular, the requirements for the pulse generator are the most stringent, which demand optical pulses with a pulsewidth less than 3 ps and an extinction ratio of more than 30 dB to avoid intersymbol interference when optically multiplexed to 160 Gb/s. Currently, these requirements can only be satisfied with two EAMs in a tandem configuration [1], [2] or one EAM followed by a 2R regenerator [1], both degrading the compactness of the pulse generator.

Recently, we reported on 40-GHz optical pulse generation using only one traveling-wave EAM with an improved quantum-well design. The traveling-wave operation of the device was demonstrated experimentally and supported by a theoretical model [3]. The pulsewidth and the output power of the generated pulses are found to be limited by the microwave amplitude inside the EAM, which is lower than the applied amplitude due to the microwave coupling loss. To increase the microwave amplitude in the device, a dual-drive scheme [4] was proposed where two synchronized microwave amplifiers with a proper phase relation are used to drive the EAM from both ends of the coplanar waveguide (CPW) line. Equivalently, the dual-drive scheme forms a standing-wave pattern along the CPW line and thus increases the microwave swing in the active waveguide.

In this letter, we propose a novel standing-wave enhanced mode of the EAM that can reduce both the number of high-frequency amplifiers and the number of microwave connections by half when compared to the dual-drive scheme [4]. This can greatly reduce the system complexity and cost. A comprehensive theory is presented to model the standing-wave operation. The good agreement between theory and experiment verifies the operation of this new design. The distributed effect, which is very critical in the high-frequency operation of the EAM, is clearly demonstrated in this work. Recently, we also demonstrated using the standing-wave enhanced mode to reduced the required microwave driving voltage for 80- to 10-Gb/s OTDM demultiplexing [5]. We believe that this newly proposed design will have a far reaching impact on a wide range of single-frequency operations.

II. Standing-Wave Mode and Theoretical Model

The EAM used in this study has traveling-wave electrodes (CPW lines). For the transverse magnetic (TM) mode, the average modulation efficiency is over 20 dB/V in the 0 to 2 V reverse bias region and the total extinction ratio can be as high as 47 dB [3], [6]. The EAM is 300 μm long and the CPW line is 1000 μm from one end to the other. As illustrated in Fig. 1(a), the proposed design forms a standing-wave pattern in the device by leaving the termination end of the CPW line open, which reflects the microwave back to the active waveguide. Since the 40-GHz microwave wavelength in the EAM (1400 μm for the active waveguide and 3000 μm for the CPW lines) is comparable to the device dimension, the phase of the standing-wave pattern must be adjusted properly so that the microwave distribution in the active waveguide is optimal. This is done by

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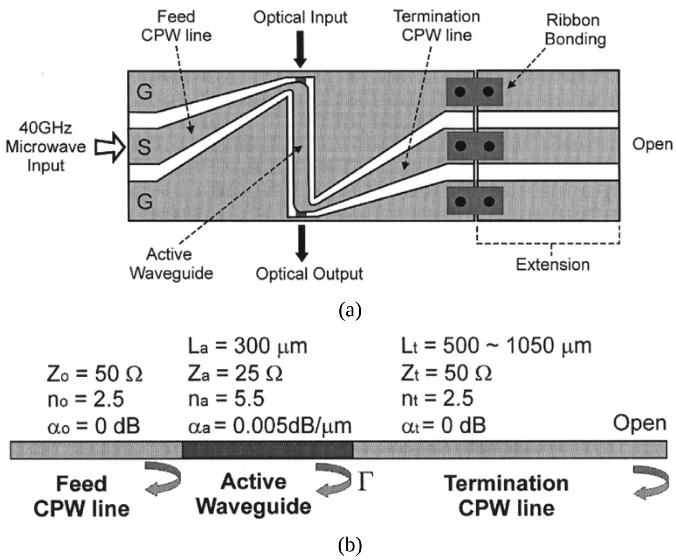

Fig. 1. (a) Schematic plot of the EAM in the standing-wave enhanced mode. (b) Microwave transmission line and the related parameters in the theoretical model.

changing the length of the termination CPW line with a bonded extension.

A theoretical model based on the transmission theory is developed to simulate the device operation, taking distributed effects into account [3], [7]. In this model, the traveling-wave electrodes of the EAM are modeled by three sections of transmission line, each with different microwave properties, as shown in Fig. 1(b). The microwave parameters are obtained from S-parameter measurements. The microwave voltage distribution in the active waveguide can be expressed as

$$\mathrm{V(z,t)} = \mathrm{V}^{+} \cdot \mathrm{Re}[\mathrm{e}^{\mathrm{j}\omega \mathrm{t}} \cdot (\mathrm{e}^{\gamma \cdot \mathrm{z}} + \Gamma \cdot \mathrm{e}^{\gamma \cdot (\mathrm{z} - 2 \cdot \mathrm{L_a})})] \qquad (1)$$

where V^{+} is the amplitude of the forward-propagating microwave; Γ is the reflection coefficient at the end of the active waveguide which depends on $\mathrm{L_t}$, the termination CPW line length; γ is the complex propagation constant; and z is the position in the active waveguide. The open at the end of the termination CPW line is assumed to be ideal. The instantaneous optical output power can be derived by summing over all the losses the lightwave encountered during the propagation through the active waveguide

$$\mathrm{P(t)} = \mathrm{P_{in}} \cdot \exp\left[-\int_0^{\mathrm{L_a}} \Delta\alpha(\mathrm{z,t'}) \cdot \mathrm{dz}\right] \qquad (2)$$

where $\mathrm{P_{in}}$ is the initial optical power, $\mathrm{L_a}$ is the length of the active waveguide, $\mathrm{t'}$ is the time when the lightwave propagates to position z, and $\Delta\alpha$ is the incremental loss at position z which can be obtained from Fig. 1 in [3] as a function of local voltage. The local voltage is the sum of the bias voltage and the microwave voltage. Only V^{+} and $\mathrm{L_t}$ are adjusted to match the

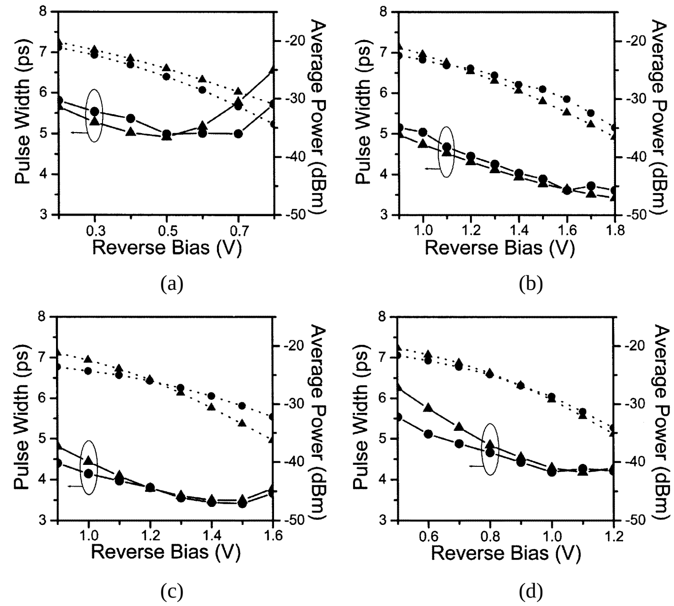

Fig. 2. Pulsewidth and the average power of the generated pulses obtained from the experiment (circle) and the theory (triangle) for the four devices: (a) $\mathrm{L_t} = 510\ \mu$m, Vpp $= 2.8$ V; (b) $\mathrm{L_t} = 790\ \mu$m, Vpp $= 2.4$ V; (c) $\mathrm{L_t} = 980\ \mu$m, Vpp $= 1.5$ V; and (d) $\mathrm{L_t} = 1050\ \mu$m, Vpp $= 1.0$ V. Solid lines: pulsewidth. Dotted lines: average power.

experimental results, which, respectively, accounts for the microwave coupling loss and the uncertainty in $\mathrm{L_t}$ due to the ribbon bonding and possible imperfections of the open.

III. Results and Discussion

Four devices are prepared with different extension lengths, ranging from 0 to 750 μm. A 2-dBm continuous wave (CW) optical input at 1555 nm and a 5.6-Vpp microwave input at 40 GHz are sent into the EAM. The average power of the output pulse is measured directly while two stages of EDFA preamplification are used to measure the pulsewidth with an autocorrelator. The absorption curve which determines the relationship between $\Delta\alpha$ and the local voltage, is measured for each EAM individually even though there are only minor differences in the high extinction (high bias) region, which can be attributed to the coupling of substrate modes. The experimental and the theoretical results for the four devices are shown in Fig. 2, in the order of increasing extension length. Close agreement between the theory and the experiment is observed. The shortest pulse generated is 3.4 ps. The termination CPW line length $\mathrm{L_t}$ obtained by matching the experimental results with the theoretical model is 510, 790, 980, and 1050 μm for the four devices, respectively. The peak-to-peak amplitude of the forward-propagating microwave $(2\mathrm{V}^{+})$ can also be obtained, which is 2.8, 2.4, 1.5, and 1.0 $\mathrm{V_{pp}}$, respectively.

An interesting point of these results is that the EAM with 1.5 $\mathrm{V_{pp}}$ microwave amplitude performs better than the EAMs with higher microwave amplitudes, in terms of the shortest possible pulsewidth and the power level with the same pulsewidth. This can only be explained by the distributed effect as shown in Fig. 3. In this figure, the microwave envelope along the active

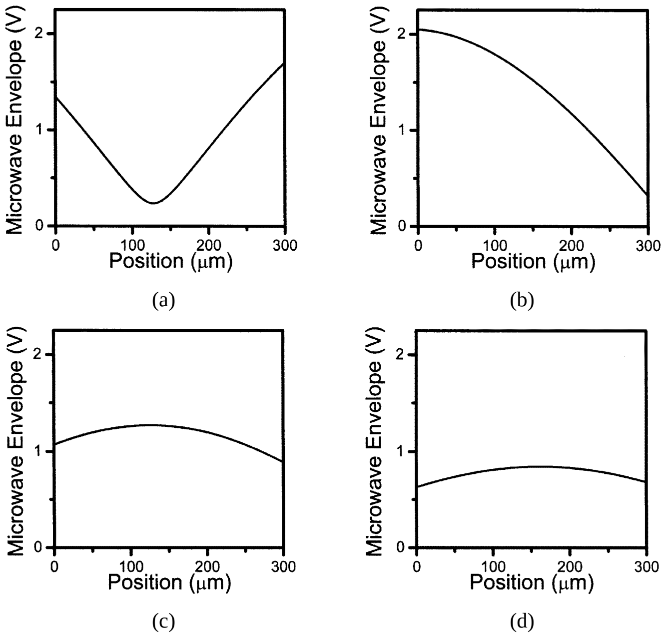

Fig. 3. Microwave envelope in the active waveguide obtained by matching the experimental results with the theoretical model for the four devices: (a) $L_t = 510\,\mu m$, Vpp $= 2.8$ V; (b) $L_t = 790\,\mu m$, Vpp $= 2.4$ V; (c) $L_t = 980\,\mu m$, Vpp $= 1.5$ V; and (d) $L_t = 1050\,\mu m$, Vpp $= 1.0$ V.

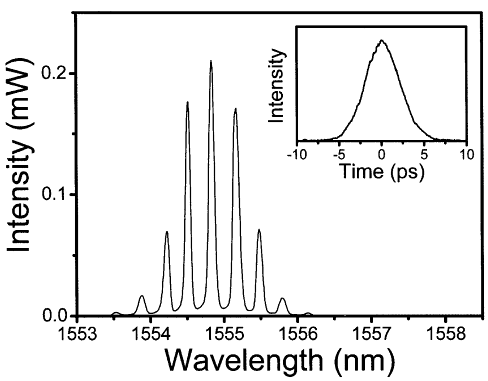

Fig. 4. Optical spectrum of the pulse train generated by the EAM with $L_t = 790\ \mu m$ at 1.8 V reverse bias. Insert: corresponding autocorrelation trace.

waveguide is plotted for the four EAMs. Even though the EAMs with 510- and 790-μm termination CPW line lengths have higher microwave amplitudes, their microwave distributions are extremely uneven, which makes it impossible to find one optimal bias voltage for different portions of the active waveguide. The device with 1050-μm termination CPW line length has a very even microwave distribution but its microwave amplitude is the lowest due to the microwave coupling loss. Fig. 4 shows a typical optical spectrum and the autocorrelation trace for the generated 40-GHz pulses. The measured time-bandwidth product is around 0.43, which is very close to a transform-limited Gaussian pulse.

Since the theoretical model matches the experiment well, it can be used to predict the performance of the EAM. Fig. 5 shows

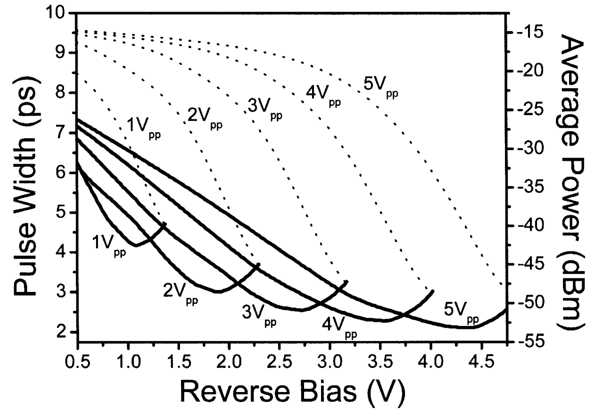

Fig. 5. Theoretical predictions for the EAM with $L_t = 1050\,\mu m$ at different microwave amplitudes $(2V^+)$. Solid lines: pulsewidth. Dotted lines: average power.

both the pulsewidth and the average power of the EAM with 1050-μm termination CPW line length at several microwave amplitudes. To generate less than 3-ps pulses, the peak-to-peak microwave amplitude has to be over 2 V. This can be done with a higher driving power or an impedance matching network at the microwave input port.

IV. Conclusion

In conclusion, a novel standing-wave mode of the electroabsorption modulator is proposed and demonstrated to generate short optical pulses at 40 GHz. A theoretical model is used to analyze the distributed effects in the device, which indicates the importance of choosing a proper termination length for the 40-GHz pulse generation. The proposed design can also be applied to other single frequency applications such as optical demultiplexing and clock recovery in a 160-Gb/s OTDM system.

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