# A SLOW-WAVE RESONANT ELECTRODE DESIGN FOR OPTICAL MODULATORS

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## ABSTRACT

A slow-wave resonant electrode structure is proposed for the phase velocity matching between the RF wave and optical signal in III-V optical modulators. The resonant structure should result in reduced RF drive requirements for the modulator.

## INTRODUCTION

It is well known that efficiency and bandwidth of traveling-wave electro-optic modulators are limited by the mismatch of the optical and electrical phase velocities. The phase difference between two waves caused by this velocity mismatch requires a short interaction length, which results in an increase of the RF drive level requirement for adequately modulation. To lower the drive voltage and power, a long device length is required. However, whithout velocity matching, the run-out limits the device length. Most broad-band modulators reported to date [1-2] still require high drive power.

Any phase velocity mismatch causes the optical phase front to walk-off from the electrical phase front. The optical lag will vary sinusoidally with this walk-off and modulation will cancel out altogether if the mismatch is severe enough or if the interaction length is too long. Since the optical phase velocity is constrained by the material indices and the waveguide structure, thus, only the electrical phase velocity can be adjusted for velocity-matching. Since the electrical phase velocity in III-V semiconductor structures is larger than the optical phase velocity, we, therefore, design a slow wave electrode structure to reduce this difference.

A new state-of-the-art design of slow wave periodic structure is proposed. For the planar structure, the proposed velocity-matched electrode configuration employs a coplanar waveguide (CPW) design as shown in Fig. 1, which consists of the usual center conductor segmented into a series of Z-shaped cascaded resonators. A similar electrode design may be used for III-V semiconductor ridge guides. With this design, the effective quality factor, Q, of the resonant structure will result in a decrease of the drive voltage. Thus, the power requirement can be reduced by a factor of $Q^2$ for a bandwidth of 10%. In addition, the bandwidth design can be improved by using Chebyshev design for coupled-line filters.

The emphasis in this paper is to demonstrate that the reduction of RF phase velocity can be achieved. Thus, we will not discuss any further the propagation losses in this structure, or the power reduction that may be achieved.

## ANALYSIS AND SIMULATIONS

The general physical configuration of the coupled-line bandpass filter, which forms the bases of the proposed structure, is illustrated in Fig. 2a. Consider the case of a parallel coupled directional coupler, for a $V_0$ voltage incident at port 1 and a matched load terminating port 4, the voltage at ports 2 and 3 are given in [3]. $V_2$ and $V_3$ may be regarded as the voltages of the waves incident onto the open-circuit terminations at their respective port. Now, $V_2$ and $V_3$ are reflected from the open circuits with a phase change of 0° and may be regarded as an incident waves at port 2 and port 3. Because of the matched termination at port 4, V4 does not produce a reflected wave at this port. Thus, the outward voltages gives

$$V_1 = \frac{V_0^2}{D}\left(1 - k_{12} - k_{12}^2 \sin^2\theta\right) \quad (1a)$$

$$V_4 = \frac{V_0^2}{\Delta}\left(2jk_{12}\sqrt{1-k_{12}^2}\,\sin\theta\right) \quad (1b)$$

where

$$\Delta = \left(\left(1-k_{12}^2\right)\cos^2\theta - \sin^2\theta\right) + j\sqrt{1-k_{12}^2}\sin 2\theta \quad (1c)$$

where $\theta = 2\pi l/\lambda$, and $k_{12}$ is the coupling coefficient. For the special case of $l = \lambda/4$, (1b) gives the phase delay of -90°. When θ is small, $\sin\theta \approx \theta$ and $\cos\theta \approx 1$, voltage at port 4 is j times a constant, or the outward phase response at port 4 is advanced by 90°.

We have performed simulations of coupled-line structure with extensions, as shown in Fig. 2b, which constitutes a component of resonant structure, based on the CAD program Touchstone. The resonators were λ long at 4.4GHz, and the phase velocities are plotted for various overlap length $l$. v0 is the phase velocity of RF signal traveling through a line with the same length as coupled-line with extensions. We note that the phase velocity leads to phase of up to 90° for overlap length $l \le \lambda/4$, which is due to the strong lumped capacitive coupling. As we increase the overlap length, the distributed capacitive coupling starts taking over unil the overlap reaches to λ/4, at which length, the phase delay is 90° and thus the velocity ratio of $v/v_o$ is unity over this coupled length. With further increase in overlap, the phase delay increases and thus the velocity ratio over the coupled length becomes less than one, and when the overlap reaches

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to $\lambda/2$ where the additional phase delay over the coupling length lags by 90°. If this distrubuted capacitive coupling can be enhanced with inductive coupling by bridging the gap, then the phase velocity reduction would be possible with such coupling even in the first $\lambda/4$ overlap region. In Fig. 3, we have used coupling coefficient $k_{12} = 0.36$. Simulation results by using Touchstone simulation program are in good agreement with equation (1b). Because the coupling is both capacitive and inductive and existing theory is not capable of analyzing this structure, we have, therefore, used this simulation program for the remainder of the study.

The proposed resonant slow-wave structure, as shown in Fig. 1, is formed by cascading a series of Z-shaped resonators with length $\lambda$, and each resonator is equally spaced by a gap g, and is connected by a narrow strip line over the overlap section to allow for dc biasing of the structure. A mixed lumped-distributed equivalent circuit model, as shown in Fig. 4, is developed by taking into account all possible coupling effect. The inductance LL is due to the discontinuities in the Z section of the resonator and its value is estimated to be LL = 0.6nH. A gap discontinuiy, g, between two adjacent resonators is introduced to provide a capacitive reactance, and the total capacitive coupling is represented by an equivalent circuit which is a $\pi$-network of three capacitances. The dc inductive strip line is represented by a single inductance, $L_{dc} = 1.6$nH. The value is optimized over a 1GHz band with other calculated parameters to match the center freqency at 4.4GHz using the EEs of Touchstone program.

## EXPERIMENTAL RESULTS

Only the phase de-embedding for characterizing the device-under-test is considered in this paper. The test fixture, made of RT/duroid 5880, $\varepsilon_r = 2.2$, with the CPW through line on 0.06-in thick RT/duroid 6002 substrate, $\varepsilon_r = 2.94$, was used for measurements. A CPW through line consisting of a uniform 50-$\Omega$ CPW line with the corresponding aspect ratio of 15/17 is terminated at both ends by a 4.5-cm mobile delay-line launcher which is exicited by a SMA connector. The pair of delay-line launcher and the coaxial connectors form a part of the test fixture and are phase de-embedded for all the cases measured.

Figure 5 shows both the experimental results for three different number of cascades and the simulation results based on the equivalent circuit model. We can see that the experimental and simulation results for the phase velocity ratio from 0.7 to 0.8 agree very well in the overlap length from $0.1\lambda$ to $0.25\lambda$. This result suggest that for the GaAs/AlGaAs optical waveguide, the optical phase velocity is 2.65/3.61 times smaller than RF phase velocity, with the proposed electrode design the RF phase velocity can be reduced by simply adjusting the resonator spacing.

## CONCLUSION

We have given a description of the design of a resonant slow-wave electrode design. Although the design of the structure used in the experiment is at 4.4GHz, it can be easily scaled to higher frequencies. With the current design, the bandwidth can be increased by means of the usual coupled-line resonator Chebyshev filter design up to 50%. The experimental measurements show that phase velocity mismatch between RF signal and optical signal can be reduced by simply adjusting the resonator spacing. For the case of GaAs/AlGaAs optical waveguide, the overlap of about $0.2\lambda$ would provide the necessary velocity match.

## REFERENCES


1. R. C. Alferness, S. K. Korotky, and E. A. J. Marcatili, "Velocity-matching techniques for integrated optic traveling wave swith/modulators," *IEEE J. Quantum Electron.*, Vol. QE-20, pp. 301-309, 1984.
2. T. Yoneyama, K. Niinuma, and S. Kanno, "Velocity-matched $LiNbO_3$ waveguide optical modulator using inverted slot line " *IEEE Microwave Guided Wave Lett.*, Vol. 1, No. 8, pp.192-194, 1991.
3. E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional coupler," *IRE Transactions on Microwave Theory and Techniques*. Vol. MTT-4, pp.75-81, April, 1956.


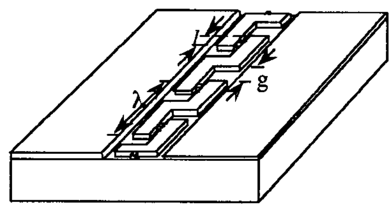


**Figure 1 Proposed Z-shaped cascaded resonant slow-wave structure**

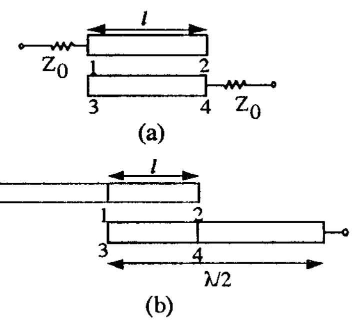


**Figure 2 (a) A coupled-line bandpass filter with variable length *l*. (b) with addition of delay line at input and output ports.**

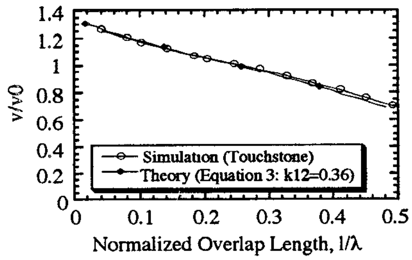


Figure 3 Velocity reduction ratio as a function of normalized overlap length

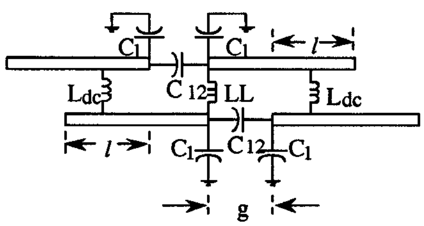


Figure 4 A lumped-distributed equivalent circuit model of slow wave structure

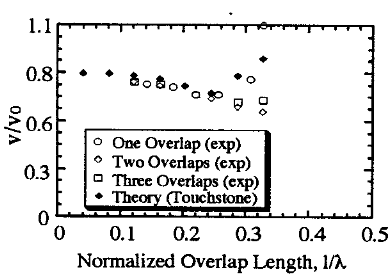


Figure 5 Velocity reduction ratio vs. normalized overlap length for both theoretical and experimental results