VELOCITY MATCHING FOR FIELD-INDUCED ELECTROOPTIC MODULATORS

F. Masot*, K.A. Remley, R. T. Kollipara, A. Weisshaar, and V.K. Tripathi

Department of Electrical and Computer Engineering
Oregon State University
Corvallis, Oregon 97331 USA

Abstract— **A capacitively loaded structure is proposed for synchronizing the microwave and optical signal in a field-induced multiple quantum well traveling-wave electrooptic modulator. The design procedure for the modulating structure is presented together with the experimental result.**

Introduction

The traveling-wave (TW) electrooptic modulator offers increased bandwidth and efficiency over other types of optical modulators, and may be readily integrated into high speed lightwave communications systems. The TW electrooptic modulator structure generally consists of a microstrip or coplanar transmission line formed directly over an optical waveguide. The electric field induced beneath the microstrip modulates the optical beam [1]. The field-induced waveguide (FIG) multiple quantum well (MQW) TW modulator was recently proposed [2]. In this structure, a DC bias electrically induces the optical waveguide by the quantum confined Stark effect (QCSE) under the Schottky contact formed by the metallization. The waveguide core consists of InGaAs MQWs separated by GaAs barriers, and the cladding layers are formed of doped GaAs/AlGaAs.

The bandwidth of TW electrooptic modulators, which may approach 40 GHz, is limited by the difference in phase velocity between the slower optical signal and the electrical signal. Several techniques have been proposed for matching the phase velocities in TW modulators, including the use of meander lines, cross-tie overlays [3], and microstrip fins [4]. The FIG MQW modulator, however, requires a straight, uniform-width microstrip supported by a longitudinally homogeneous semiconductor or dielectric material for proper optical waveguiding. Yu and Gopinath [5] have proposed the use of a capacitively loaded electrode structure to slow the RF wave in a directional coupler modulator. The present work extends this concept to a distributed capacitively loaded microstrip-type structure for attaining a desired amount of phase velocity reduction in a FIG MQW modulator.

* F. Masot is currently with the Department of Applied Physics, University of Seville, Seville, Spain

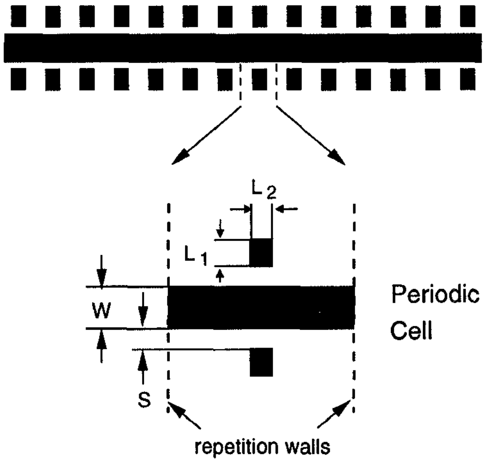

Fig. 1. Microstrip-type periodic structure under study.

Theory

The structure under study consists of a microstrip line on a GaAs substrate (ϵ_r = 12.9, thickness = 100 μm), coupled to periodically spaced conductor patches, as shown in Figure 1. Each patch introduces both self and mutual capacitances, which may be modeled as a discrete capacitance placed at even intervals along the line (Figure 2a). The global effect of patches periodically spaced on an ideal infinite-length line is to increase the distributed average capacitance from that of the unloaded microstrip line. Because the phase velocity is inversely proportional to the capacitance, the desired reduction in phase velocity may be acheived. However, the characteristic impedance will also be reduced for the same reason. The aim of this work is to match the microwave phase velocity to the phase velocity of the light in the GaAs while keeping the characteristic impedance 50 Ω, at a typical microwave operating frequency of 30 GHz. Since the phase velocity of the microwave signal in the unloaded microstrip is about 10.3 cm/ns, and the velocity of the optical signal with a free space wavelength of 1.3 μm is 8.9 cm/ns [6], the required phase velocity reduction is around 15%.

In order to investigate the ability of this structure to meet the desired design parameters, the simple equivalent circuit model in Figure 2b is employed. This "unit cell" is the

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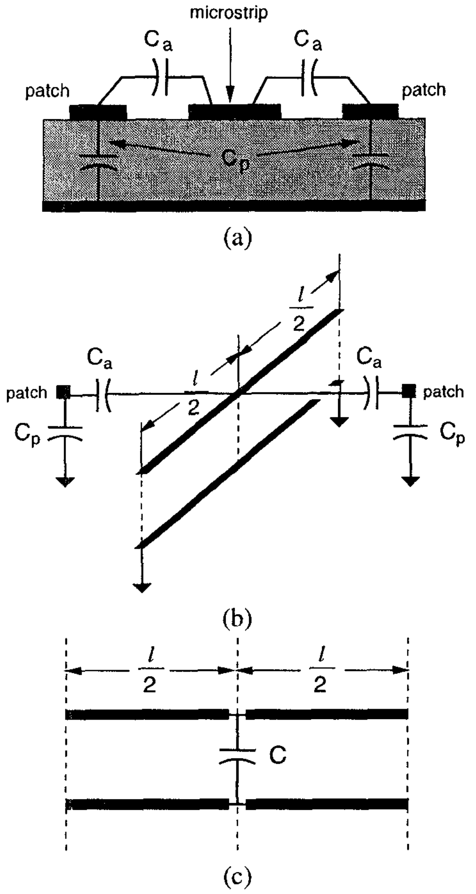

Fig. 2. Equivalent circuit model of the unit cell. (*a*) C_a is the mutual cpacitance between the microstrip and patch, and C_p is the self capacitance of the patch. (*b*) Periodic cell model used for calculating the parameters z_c^p and v_{ph}^p of the periodic structure.

equivalent circuit for one period, and this pattern is repeated along the microstrip. The values of characteristic impedance and phase velocity of the periodic structure, z_c^p and v_{ph}^p, may be obtained from the chain parameters (ABCD matrix) of the cell using transmission line theory, as in [7]:

$$z_c^p = \frac{2B}{D - A \pm \sqrt{(A+D)^2 - 1}} \quad (1a)$$

$$v_{ph}^p = \frac{2\pi f l}{\Im m\left\{\ln\left(\left(\frac{(A+D)}{2} \pm \sqrt{\frac{(A+D)}{2}^2 - 1}\right)\right)\right\}} \quad (1b)$$

where $\Im m$ represents the imaginary part, l is the physical length of the cell (distance between consecutive patches), and f is the frequency of operation (here, 30 GHz).

The chain parameters ABCD of the cell are readily expressed in terms of characteristic impedance Z_c and effective permittivity ϵ_{eff} of the section of unloaded microstrip inside the cell, the value of the capacitance C, and the length l of the cell.

The electrical parameters of the unloaded microstrip (Z_c and ϵ_{eff}) have been computed considering the dispersion in frequency at 30 GHz. This has been done by means of an efficient full-wave analysis carried out in the spectral domain [8]. The dispersion due to the periodicity of the loaded structure can be neglected for frequencies below 100 GHz if the size of the period is chosen small enough (in this work, around 50 μm) [6].

Several values for the static capacitance between one patch and a microstrip line for different patch geometries (from square to rectangular) are shown in Table I. The effect of spacing between microstrip and patch for square patches is shown in Table II. C is the global capacitance of each pair of patches, and $C = \frac{2C_aC_p}{C_a+C_p}$ (refer to Figure 2a). These capacitance values have been computed by an integral equation method for the charge distribution on the patches and microstrip. The integral equation is solved using an iterative approach, in this case, the generalized biconjugated gradient method in combination with FFT algorithms [9]. In this study, the capacitance between two consecutive patches is neglected. This approximation is reasonable if the distance between patches l is small compared to the wavelength. The patches in this case are approximately at the same potential.

TABLE I

Capacitance values C_a and C_p of the model in Figure 2a, and C of the model in Figure 2b.

$L_1(\mu m)$	C_a (fF)	C_p (fF)	C (fF)
10	1.32	1.76	1.51
15	1.52	2.31	1.84
20	1.70	2.85	2.13
25	1.80	3.38	2.67
30	1.89	3.90	2.86

TABLE II

Capacitances C_a, C_p, and C for different spacing widths S between microstrip and square $10\mu m \times 10\mu m$ patches.

$S(\mu m)$	C_a (fF)	C_p (fF)	C (fF)
5	1.70	1.54	1.62
10	1.32	1.76	1.51
15	1.08	1.93	1.39
20	0.91	2.07	1.26
25	0.78	2.18	1.15

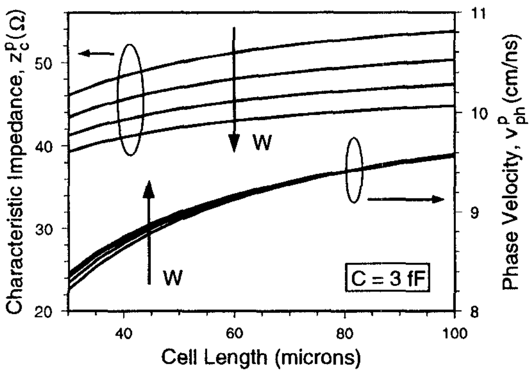

Fig. 3. Characteristic impedance, z_c^p, and phase velocity, v_{ph}^p, of the periodic structure versus length, l, of the cell for microstrip widths of w = 50μm, 60μm, 70μm, and 80μm.

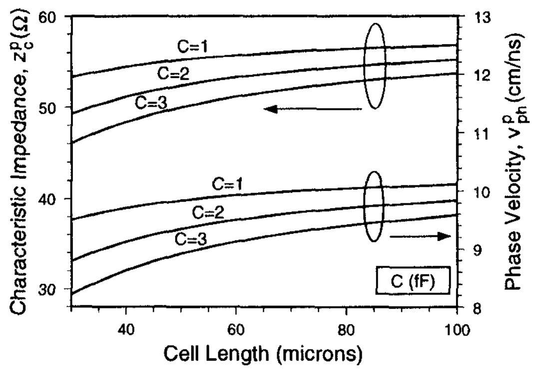

Fig. 5. Characteristic impedance, z_c^p, and phase velocity, v_{ph}^p, of the periodic structure versus the length, l, of the repetition cell. Here w = 50μm.

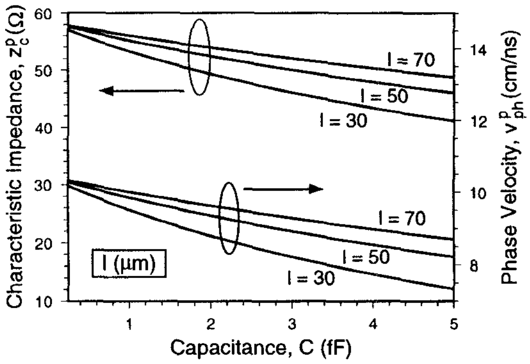

Fig. 4. Characteristic impedance, z_c^p, and phase velocity, v_{ph}^p, of the periodic structure versus the capacitance C.

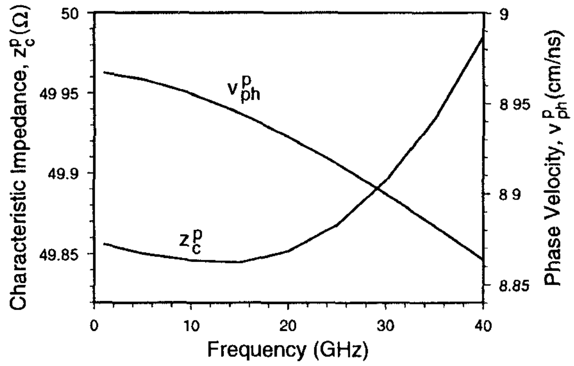

Fig. 6. Characteristic impedance, z_c^p, and phase velocity, v_{ph}^p, of the periodic structure as a function of the frequency, for the optimum design C=1.84 fF, l = 30μm, and w = 50μm.

Computational Results

The behavior of the characteristic impedance z_c^p and phase velocity v_{ph}^p of the slow wave microstrip for several values of the microstrip width with a value of C=3 fF are shown in Figure 3a and 3b. Figure 3 shows that in order for z_c^p to be in the desired range of 50 Ω with capacitive loading of 3 fF, the strip width would be 50 μm. This corresponds to about 58 Ω of the unloaded microstrip.

For such a microstrip line (50 μm width), the desired reduction in phase velocity and the exact value of 50Ω can be achieved simutaneously by adjusting the capacitance value C and/or the distance l between consecutive patches. This can be seen in Figures 4 and 5.

The optimum values of capacitance and length for realizing the desired requirements (50 Ω, 8.9 cm/ns) has been obtained by a simple optimization procedure. In this procedure, two error functions have been minimized:

$$F_z(l,C) \;=\; (z_c^p(l,C)/Z_0 - 1) \qquad (2a)$$

$$F_v(l,C) \;=\; (v_{ph}^p(l,C)/V_{pi} - 1) \qquad (2b)$$

where Z_0 and V_{pi} are the required characteristic values, in our case, $Z_0 = 50\ \Omega$ and $V_{pi} = 8.9$ cm/ns, z_c^p and v_{ph}^p are the characteristic impedance and phase velocity of the periodic slow wave structure. z_c^p and v_{ph}^p are functions of the capacitance C and length l. The optimization procedure is a simple one based on tangent outline (similar to the one reported in [10]). The result of this optimization at 30 GHz for a 50 μm microstrip on GaAs gives an optimum value of capacitance C=1.84 fF and length l=30 μm, which correspond to $z_c^p = 49.90\ \Omega$ and $v_{ph}^p = 8.9$ cm/ns. This value of C can be obtained, for instance, with the rectangular patch geometry in Table I corresponding to $L_1 = 15\ \mu$m ($L_2 = S = 10\ \mu$m).

Figure 6 shows the frequency response of the periodic structure for the above optimum design. In this figure, it is clear that z_c^p and v_{ph}^p are maintained close to the desired values Z_0 and V_{pi} with an error below 1% in the whole

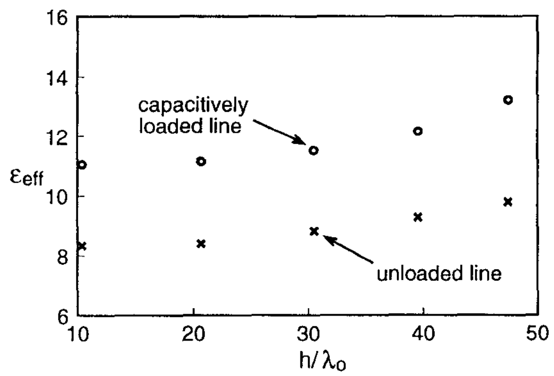

Fig 7. Comparison of the effective dielectric constant of the periodically loaded and unloaded structures.

band. This is important since the mismatch in any of these parameters reduces the bandwidth of the modulator [11].

Experiment

To experimentally verify the reduction in phase velocity, a scaled version of the proposed structure model was fabricated. A comparison of the effective dielectric constants of the unloaded and loaded structures is shown in Figure 7. It may be seen that the slowing of the phase velocity is nearly uniform (to within 1%) over a broad frequency range when compared to the unloaded structure.

Conclusion

In conclusion, a technique for broadband design of a field-induced traveling-wave electroooptic modulator has been presented. The design procedure has been validated by rigorous simulations as well as measurements.

Acknowlegements

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