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# Velocity Matched Electrode Structures on Doped Semiconductors for Large Bandwidth Optoelectronic Modulators*

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High-speed optoelectronic modulators are becoming increasingly important in microwave applications. These devices are necessarily electrically large and hence require velocity matching of the microwave signal to the light. A design methodology for velocity matched electrodes on doped semiconductor devices will be presented. As an example of a successful device design, experimental results on a >10 GHz bandwidth high-efficiency (>15°/V/mm) Mach Zehnder interferometer will be presented.

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High-speed optoelectronic modulators are becoming increasingly important in future microwave applications. Due to the weak interaction of light with the microwave drive signal, practical optoelectronic modulators are necessarily large. Device lengths of millimeters to centimeters are common. High-speed operation therefore requires a velocity match of the microwave signal to the light.

Velocity matching in undoped or low doped semiconductor optoelectronic modulators typically involves finding a way to slow down the electrical signal. Several successful techniques have been developed, but undoped structures offer very low electrooptic efficiency which results in undesirably large devices which are not amenable to integration. Additionally, these modulators commonly require large microwave drive levels. To overcome these limitations, doped semiconductor structures can increase modulation efficiency by several orders of magnitude.

Appropriate doping within the semiconductor localizes internal electric fields which results in a better overlap with the optical signal and hence a much higher electrooptic efficiency. The more localized the light and electric field become the higher the phase shift per applied voltage. Unfortunately, localization of the electric field also results in a larger device capacitance. This results in slow-wave propagation along the device making velocity matching difficult. Therefore, the problem with doped structures is generally the opposite of undoped structures as a velocity increase is necessary in the design. Propagation along slow-wave doped structures has been extensively analyzed. Rather than a detailed *analysis* of these structures, this paper will discuss the *design* of velocity matched electrode structures with careful consideration for the needs of the optical aspects of the problem.

A cross-section of a high-efficiency phase modulator based on a slow-wave coplanar waveguide design is shown in Fig. 1. This modulator design has been incorporated in a Mach-Zehnder intensity modulator design and measured to have a bandwidth in excess of 10 GHz. A device length of 1 mm gives a $V_\pi$ of about 10V. Fig. 2 shows plots of RF index and characteristic impedance. These plots show a reasonable correspondence between theory and experiment. The measured RF index, though a bit high, represents an adequate velocity match for the short lengths required in using these high-efficiency modulators. The RF loss was measured to be about 1.5 dB/mm at 10 GHz compared to a theoretical value of 0.6 dB/mm.

In this paper, a design methodology for velocity matched electrodes on doped semiconductor devices will be presented. Bandwidth and optical phase shift performance tradeoffs will be developed for doped semiconductor optoelectronic modulators. As an example of a successful device design, experimental results on a >10 GHz bandwidth high-efficiency (>15°/V/mm) will be presented.

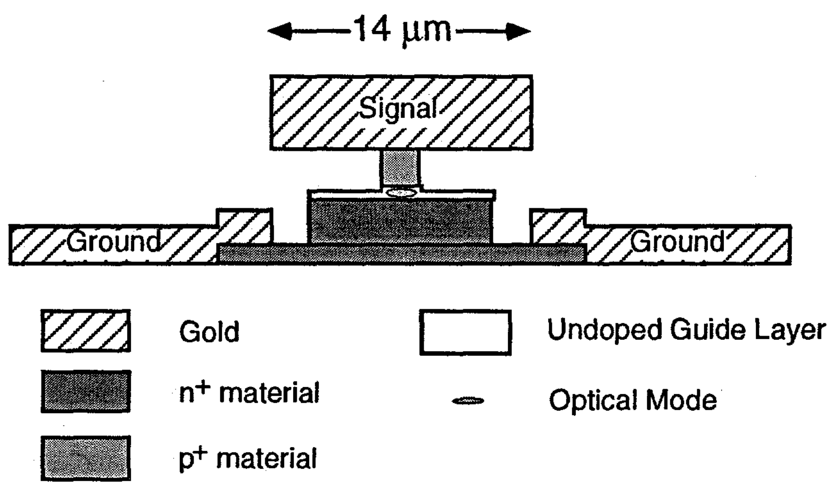


Fig. 1. Cross-section of a velocity matched doped optical phase modulator (0.6 µm depletion layer). Drawn to scale.

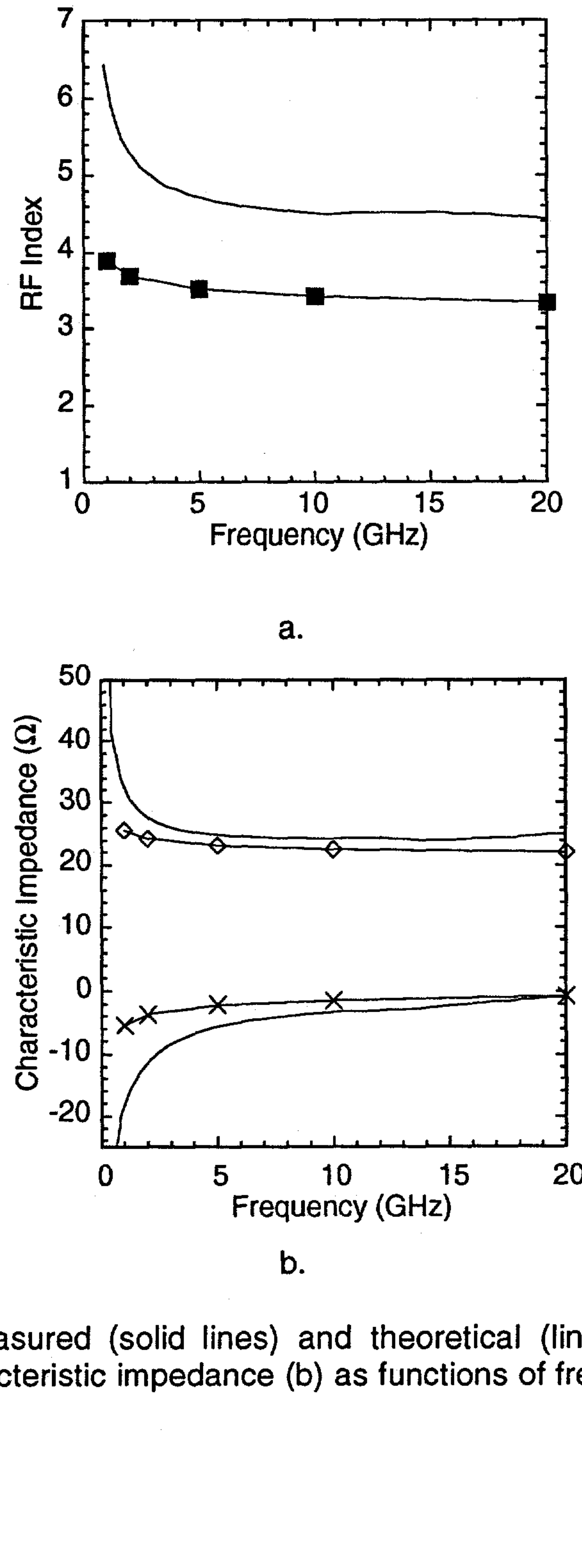


Fig. 2. Plots of measured (solid lines) and theoretical (lines w/ symbols) RF index (a) and characteristic impedance (b) as functions of frequency.