Design and On-wafer Testing of Millimeter-Wave External Optical Modulators

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Abstract - Highly accurate computation of the microwave refractive index and impedance of the coplanar waveguides on Ti:LiNbO3, Mach-Zehnder external optical modulators is performed using the extended spectral domain approach. Narrowband millimeter-wave modulators based on these calculations have been designed, fabricated, and tested with a novel on-wafer, 0-40GHz, optical and electrical probe station.

Introduction

Future millimeter-wave fiber optic links will require narrow data bandwidths centered around a millimeter-wave carrier [1] [2]. By designing narrowband external optical modulators (EOM), the performance of the optical transmitter typically shows better results than those achieved with a wideband EOM. Of the possible narrowband EOM designs, which include a periodic phase shifted and intermittent interaction traveling waveguides (TW) and resonant lines design, the first is the most appropriate for millimeter-wave frequencies because it has the lowest insertion loss and very-long interaction length. However, the microwave refractive index of the microwave waveguide must be known precisely in order to calculate the required phase shift length for a desired carrier frequency [3].The extended spectral domain approach (ESDA) was used to accurately calculate the microwave refractive index of a coplanar transmission line of finite thickness fabricated on an anisotropic, multi-layered dielectric [4].This paper presents the design and characterization method for a Mach-Zehnder EOM, which can be used to provide high carrier frequencies.

Velocity-Matching Techniques

Particular attention is needed when designing the EOM electrode. At MMW frequencies, a travelling wave Mach-Zehnder design is most practical, as opposed to a lower frequency lumped-electrode design. However, the primary concern when using the TW electrode is the velocity mismatch between the propagating optical and microwave signals. To achieve a velocity match, the microwave signal must see an effective

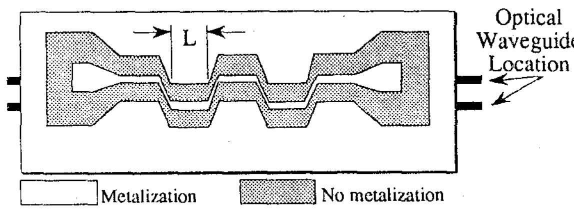

Fig. 1 Phase shifted electrode concept. CPW probe contacts are on either side of line.

microwave refractive index equal to the optical refractive index (approx. 2.2 for LiNb03). If the velocities are not equal, the effective modulation is reduced, and for certain combinations of frequency and electrode length, the modulation response can be zero. In the MMW bands, RF attenuation in the conductor (electrode) also needs to be considered as a factor which limits in transmission line length.

To optimize these parameters, and hence the modulation characteristics, it is necessary to simultaneously choose the proper electrode type, length, operating frequency, and microwave refractive index to obtain a low drive voltage and to keep impedance mismatch to a minimum. The microwave refractive index can be controlled accurately by choosing the proper buffer layer and metalization heights [4].

To obtain a high-efficient EOM which operates at MMW frequencies, a TW electrode is chosen. Additionally, the electrodes are designed to periodically reverse the microwave phase to artificially induce velocity matching at a desired carrier frequency [3] (see Fig. 1). Since there is no need to make the buffer or metalization layer very thick (to increase the microwave velocity), the thin layered structure can be used. This produces several benefits.

One advantage is the increase in the electric field below the electrodes and in the LiNbO3, which increases the effective microwave refractive index. By employing counter-propagating waves,very short interaction segments can be used. Because these segments are less than a few millimeters in length (as compared to co-propagating waves which have segments greater than several millimeters), an optimum

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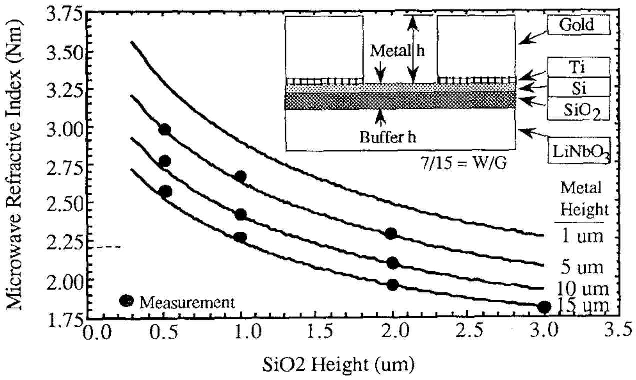

Fig. 2 Microwave refractive indexes with ESDA calculations and from measurement for ten wafers, and diagram showing the structure used for the calculations.

length for the best trade-off between driving voltage and RF attenuation can be chosen.

Since a particular length is likely to have more segments than when using co-propagating waves, improved modulation response can be expected at the design frequency. This is because the design is inherently band-limited (an infinite amount of segments would yield zero bandwidth) and the response improves as the number of phase shift segments increases (under conditions of no RF attenuation).

Electrode Design

The main parameter which is required to calculate the segment length is the effective microwave refractive index seen by the electromagnetic TW. Once this value is known precisely, the design process can proceed. Although it is possible to make several wafers, each with different parameters, and then test their characteristics, it would be less time consuming and expensive if an accurate theoretical model could be developed.

Models have been developed previously with varying degrees of success [5]. The best and most accurate method to date includes the metalization height as a parameter in the microwave index, impedance and loss calculations. This is called the Extended Spectral Domain Approach (ESDA) [4]. By having an accurate knowledge of each layer's thickness and dielectric constant or resistivity on the wafer, this method can accurately predict the microwave refractive index, impedance and rf loss (see material layers in Fig. 2).

To verify this method's predictions, a series of wafers with various height combinations of metalization and buffer layers are fabricated and tested with a Network Analyzer and a microwave probe station. Various co-planar waveguide (CPW) lines and structures are fabricated on the wafer to allow char-

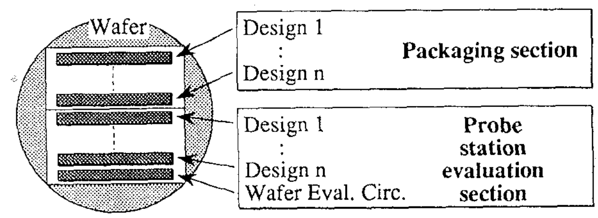

Fig. 3 General layout of the millimeter-wave EOM wafer.

acterization of several parameters. These test wafers contain no optical waveguides.

Measurements of refractive index are accomplished by using time domain reflectrometry (TDR) and line resonance frequency techniques. Additionally, DC resistivity, return loss, and insertion loss for representative transmission line structures are evaluated. The results are compared to the theoretical predictions made using the ESDA. Several representative values are shown in Fig. 2. The predicted values of microwave refractive indexes agree very well with the measured values. Possible sources of error are attributed to the resolution of the measurement processes as well as to variations in the fabrication processes.

Since an accurate model is now available for electrode characterization, it is a simple matter to evaluate various electrode structures without the need to experimentally verify each design. Additionally, for the phase reversal type electrode structures, the design accuracy is improved through use of the knowledge of the exact microwave refractive index.

Optical MMW On-Wafer Probe Station

To test the modulation capabilities of EOMs, the processed LiNb03 crystal typically is packaged within a microwave housing by using coaxial connectors. Optical fibers are also pigtailed to the ends of the crystal's waveguide. Once finished, this module is essentially the final packaged EOM and is ready for testing. However unless the design or fabrication process is flawless, much time could be spent in vain mounting and testing poor circuits.

What has therefore been developed is a method of testing the performance of the EOM without the need to first package the crystal and mount the fibers (which saves a considerable amount of time). This circumvents the crystal dicing, mounting, and fiber epoxying steps and also eliminates the need to attach the microwave connectors.

This is accomplished by dividing the wafer's circuit design area into two sections: one with circuits for final packaging and the other with circuits to be evaluated with a microwave probe station. Each wafer contains several designs with both wafer sections having identical copies of each design. After the wafer is cut into these two sections, the half with the CPW contacts is tested with the probe station. The wafer

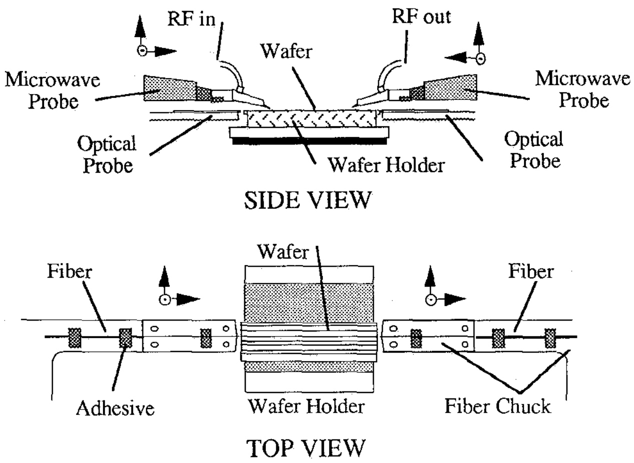

Fig. 4a Schematic diagram of modified microwave/optical probe station experimental set-up.

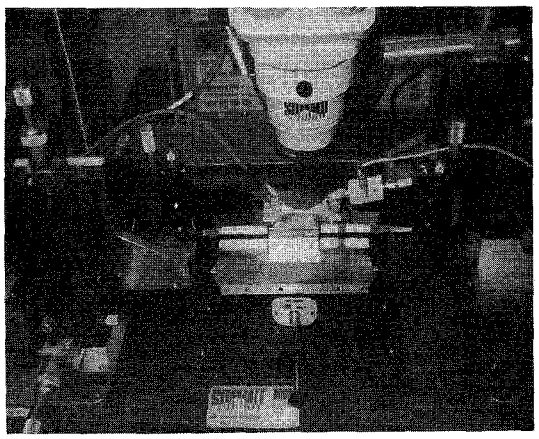

Fig. 4b Photograph of the modified probe station.

layout is shown in Fig. 3.

The probe station half of the wafer is tested with a modified microwave probe station which includes the addition of two horizontal, SM fiber optic probes as well as modifications to the existing microwave probes (see Fig. 4a and 4b). In this way, the calibrated electrical and electrooptical characteristics of the wafer can be simultaneously measured. After the best performing design in a half of the wafer for on-wafer testing is determined and characterized, the corresponding design in another half of the wafer is subsequently diced and packaged. Additionally, there are several circuits on the CPW evaluation side which are used to fully evaluate the electrical properties of the LiNb03 crystal parameters for further comparisons with theoretical values.

This method also provides a method for quickly comparing a variety of new designs on one wafer. A less attractive alternative would be to load diced wafers into a universal microwave test fixture to allow a quick attachment of coax

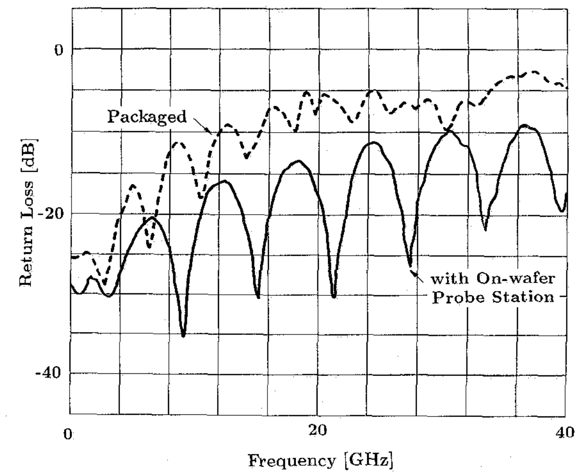

Fig. 5 Return Losses of RF input port of EOM. Solid line is for wafer EOM with On-wafer Probe Station, and broken line is for package EOM.

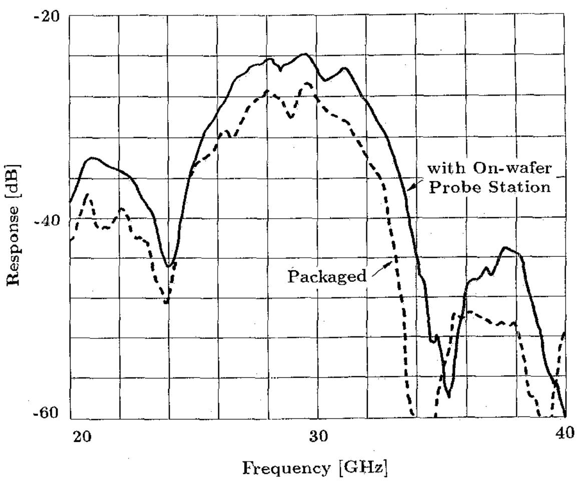

Fig. 6 Optical responses of a 30 GHz EOM. Solid line is for wafer EOM with On-wafer Probe Station, and broken line is for package EOM.

to CPW transitions. This fixture could then be used in an identical set up for further evaluation.

Testing and Characterization

Both on-wafer and packaged EOMs are characterized in the same way except as to whether they use an on-wafer probe station. The optical response of the EOM is converted into an electrical signal by a 40 GHz bandwidth photodetector. The electrical signal output from the photodetector is amplified and measured as a transmission response by a 20 - 40 GHz Network Analyzer. Before this measurement is taken, the system is calibrated for all responses except that of the photodetector. Thus, the total optical responses of the various EOMs are measured.

Fig.5 shows return loss of each EOMs which are designed as 32GHz center frequency narrow bandwidth EOMs. The packaged EOM has about 5 dB more return loss than that of on-wafer EOM because of reflection at discontinuities between connector and wafer in the packaged EOM and of infuluence of packaging (change of wave-guide impedance on the wafer and so on).

Fig.6 shows optical responses of each the EOMs. The on-wafer EOM has about 4dB better and more smooth response than that of the packaged EOM. This is caused by return loss of EOMs and means that characteristics of EOM itself can be precisely measured with optical and millimeter-wave on-wafer probe station.

Conclusion

Through accurate theoretical calculations and a novel characterization method, the design and fabrication of millimeter-wave EOMs is possible.Theoretical predictions are supported by the Extended Spectral Domain Approach for calculating RF loss, impedance and microwave refractive indexes. Measured results match these predictions very well. Likewise, the ability to test "on-wafer" designs without the need for packaging greatly reduces the design and characterization time of various EOM designs. By applying the theoretical modeling as well as the new characterization method, designs for frequencies in the millimeter-wave bands can be easily realized.

Acknowledgement

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