Novel Electroabsorption Modulator Design Based on Coplanar Waveguide Configuration

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***Abstract*—We present a new design approach for electroabsorption modulators based on integrating a microwave element monolithically with the photonic element. A new method is reported for planarizing and patterning a low-permittivity film using a hydrogen silsesquioxane spin-on coating with electron beam exposure; after 5 coating steps, the layer thickness was 6 µm. We demonstrate the design by fabricating a coplanar waveguide with a 50 Ω characteristic impedance at the input port, at operating frequencies up to 67 GHz.**

Keywords— Electroabsorption Modulator, electroabsorption modulated laser, coplanar waveguide, low-k material planarization, monolithic microwave photonic integration

I. INTRODUCTION

Electroabsorption Modulators (EAMs) based on the Quantum Confined Stark Effect (QCSE) are promising candidates for high bit-rate backbone optical fibre communication systems and for use in the more price-sensitive local area. The EAM offers a high modulation speed, low drive voltage, high extinction ratio and can be integrated monolithically with other devices, such as Distributed Feedback (DFB) Lasers in the so-called Electroabsorption Modulated Laser (EML) [1], [2], [3]. Currently, most EMLs use either a lumped or travelling-wave electrode configuration. High frequency operation of the lumped structure is limited primarily by the *RC* time constant of the circuit, with the principal contributions to the capacitance coming from the bond pad and the EAM itself. The travelling-wave design provides an efficient solution to overcome this *RC* limit by incorporating the EAM within an impedance matched transmission line [4], [5]. However, the travelling-wave option for EMLs can be very difficult to apply. This is due to size limitations, material restrictions and the complexity of the monolithic integration.

In this paper, we present a new electrode design for EAMs based on a Coplanar Waveguide (CPW) transmission line configuration. The design eliminates the circuit capacitance associated with the bond pad in the lumped approach and provides a direct probe interface to the external circuit with a 50 Ω characteristic impedance.

II. DESIGN AND MODULATION

The design is based on Monolithic Microwave Photonic Integrated Circuit (MMPIC) technology with the aim of achieving optimized interface matching between the microwave and photonic signals. The device used an AlGaInAs/InP *p-i-n* structure containing 5 Quantum Wells (QWs). AlGaInAs based QWs have a larger conduction band discontinuity and smaller valence band discontinuity compared to the more conventional InGaAsP system. This property provides higher electron confinement and a higher characteristic temperature for lasers, making the material system attractive for uncooled laser operation and improving EAM performance [1], [2].

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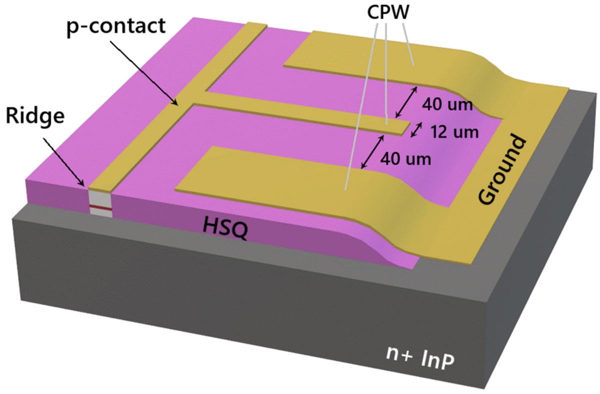

Fig. 1. The EAM design configured with CPW transmission line of 12 µm signal conductor and 40 µm signal-to-ground gap.

The design of the EAM section of the EML is illustrated in Fig. 1, where the width of the ridge waveguide is 2.5 µm. The ridge guide in the EAM section is designed to be deep etched down to the n^+-InP substrate, thus reducing the parasitic capacitance. The deep etch provides an open surface for connecting the ground of the Transmission Line (TL) to the heavily doped substrate, as illustrated in Fig. 1. The intrinsic capacitance per unit length of the EAM was estimated to be 1.4 fF µm^{-1}. The maximum (−3 dB) modulation frequency was then estimated analytically, with the results shown in Fig. 2.

Figure 2 also shows a comparison with the maximum modulation frequency that can be achieved with a conventional lumped configuration for a device designed under the same circumstances, with a 60 µm diameter circular *p*-contact pad. The analysis indicates that an increase of more than 60% in the modulation frequency can be achieved with the new design.

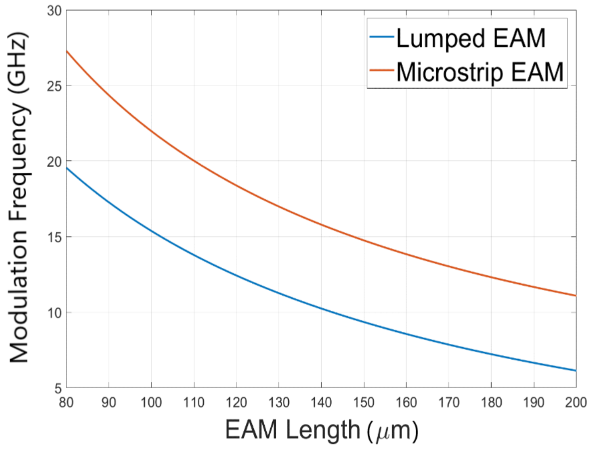

Fig. 2. Maximum (−3dB) modulation frequency as a function of EAM length for the lumped and CPW EAM configurations respectively.

The fabrication of the transmission line in the EML device requires surface planarization using low permittivity material. Conventional low permittivity planarization using Benzocyclobutene (BCB) or polyamide material becomes very difficult to apply in Photonic Integrated Circuits (PICs). These materials require many fabrication steps, a high curing temperature and their fabrication is based on photolithography rather than Electron Beam Lithography (EBL). These factors make them time-consuming to use in manufacture and feature definition has relatively lower accuracy.

Hydrogen Silsesquioxane (HSQ) is an alternative material that overcomes many of these concerns. The required HSQ film thickness was determined analytically using the following equations [6], [7], [8];

$$Z_L = \frac{60\pi}{\sqrt{\varepsilon_{r,eff}}} \times \frac{1}{\frac{K(k)}{K(k')} + \frac{K(k_1)}{K(k_1')}} \quad (1)$$

$$\varepsilon_{r,eff} = \frac{1 + \varepsilon_r \frac{K(k')K(k_1)}{K(k)K(k_1')}}{1 + \frac{K(k')K(k_1)}{K(k)K(k_1')}} \quad (2)$$

where $k = a/b$, $k' = \sqrt{1-k^2}$, $k_1 = \tanh\left(\frac{\pi a}{2h}\right) / \tanh\left(\frac{\pi b}{2h}\right)$, $k_1' = \sqrt{1-k_1^2}$, a is the centre conductor width, b is the gap spacing between the centre conductor and the ground plane, and $K(k)$ is the complete elliptical integral of the first order with modulus k. Accordingly, a thickness of 6 µm was found to be sufficient for the design for a CPW TL with a signal conductor of width 12 µm and signal-to-ground gap of 40 µm.

III. Fabrication

The design of the active cavity of the DFB laser is based on lateral guiding using a shallow etch process. An additional etch step is needed to deep etch the EAM section. The low-permittivity film required for the connection to the EAM was built up using successive HSQ spin-on coatings [9], with 5 spin coatings required to obtain a 6 µm film thickness. After each spin coating, the sample was patterned using Electron Beam (EB), followed by deposition of 40 nm of SiO_2 using Plasma-Enhanced Chemical Vapor Deposition (PECVD). The fabricated planarized film is shown in Fig. 3.

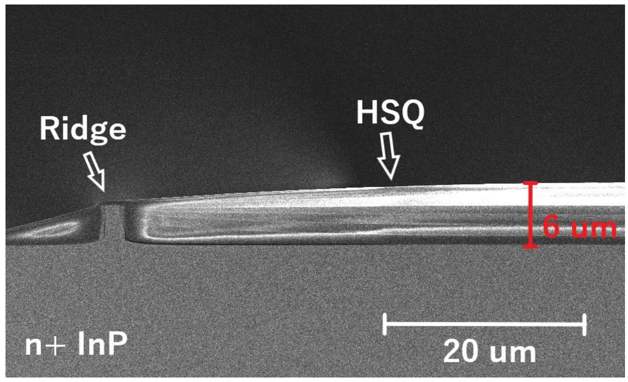

Fig. 3. A cross-section SEM image for the planarized HSQ film.

The PECVD SiO_2 layers protect the previously spun HSQ from dissolving, while the EB exposure adds the advantage of defining the shapes of the planarized structures as an integral part of the fabrication; it also avoids the need for long periods of thermal curing. Furthermore, it has been demonstrated that EB exposed HSQ-films have a relatively higher concentration of Si-H bonds compared to conventional furnace-cured HSQ-films, which indicate much better dielectric properties [10]. In order to confirm the applicability of using the planarized film for microwave technology, a CPW TL was fabricated on the film with the required signal conductor and signal to ground dimensions.

IV. Test and Measurement

Here we report electrical characterisation of the CPW section of the device. The fabricated CPW was tested using a Keysight vector network analyser (VNA) with a Cascade on-wafer semi-automated probe station. A pair of GGB microprobes with a pitch separation of 100 µm was used, and the system was calibrated using the Short-Open-Load-Thru (SOLT) method from 10 MHz to 67 GHz. The two port scattering parameter measurements for a 100-µm-long CPW are shown in Fig. 4, which indicate a port reflection lower than −20 dB over the frequency range up to 67 GHz. The insertion loss, shown in Fig. 5, rises from 1 dB mm^{-1} at low frequencies to ~5 dB mm^{-1} at 67 GHz

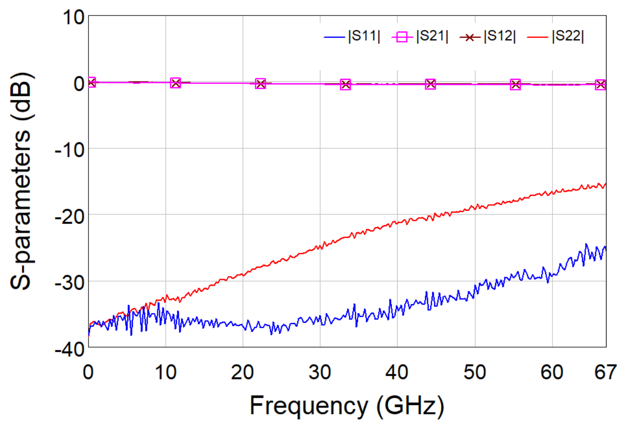

Fig. 4. Two port scattering parameter measurements for a 100-µm-long CPW.

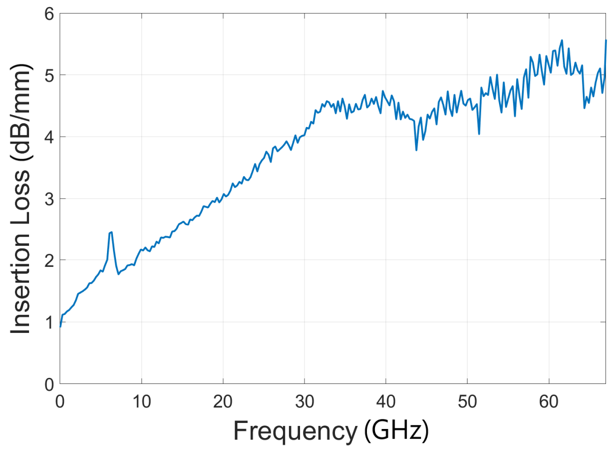

Fig. 5. The insertion loss per unit length for the transmission line.

The corresponding characteristic impedance at the input port of the CPW was calculated and is shown in Fig. 6. The results indicate a characteristic impedance in the range from 48 to 56 Ω is achieved, which agrees with the analytical calculation.

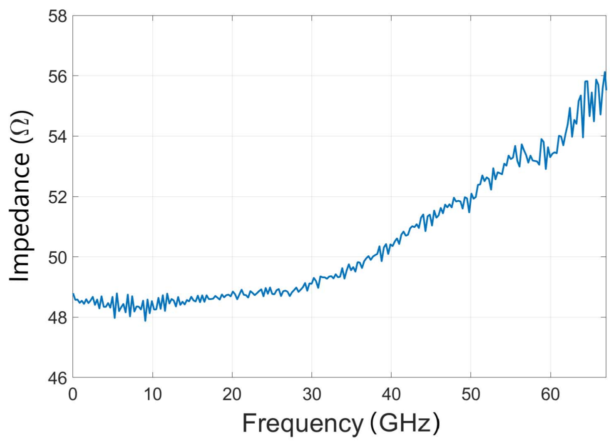

Fig. 6. Characteristic impedance at the input port of the CPW.

V. Conclusion

The new design is a promising route for achieving higher modulation speeds with a simple low-cost manufacturing process. The electrical interface provides a 50 Ω characteristic impedance, with dimensions designed for direct connection with a microwave probe. The design ensures maximum RF power is delivered to the modulator with minimum reflections at frequencies up to 67 GHz.

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