High-Speed Traveling-wave Electrodes for Polymeric Electro-Optic Modulators

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ABSTRACT

A detailed design and fabrication procedure of high-speed traveling-wave (TW) electrodes for EO polymer-based modulator has been developed. Design consideration, thick photoresist deposition and electroplating are specially focused on. A lot of practical experiences are introduced as well. This kind of modulator can be used in satellite receiver systems , remote connection of cellular radio systems ,and LANs

1. INTRODUCTION

Polymeric electro-optic modulators in the integrated-optic embodiment are the most promising candidates for wideband lightwave applications[1-5]. These devices, using advanced electro-optic (EO) polymers,exhibit wider bandwidth, lower drive power, and polarization-independent operation. Such a device has important applications not only to the military systems but also to the commercial market.

To ensure the high-speed operation of an integrated electro-optic modulator, it is mandatory to employ traveling-wave electrodes[1,5,6]. The bandwidth of the electro-optic modulator employing a traveling-wave electrode is limited by the velocity mismatch between the microwave and optical mode as well as the RF transmission loss of the electrode. Due to the intrinsic low dielectric constant of EO polymers, the modulation bandwidth of polymer-based modulators are mainly limited by the electrode transmission characteristics. Thick traveling-wave electrodes are required to reduce the microwave transmission loss and to provide the required velocity match for wideband operation.

There are two types of traveling-wave electrodes that can be implemented in practical devices. They are coplanar strip line electrodes (CPS)[7] and coplanar waveguide electrodes (CPW)[8,9]. In general, a CPS electrode has a lower transmission loss and lower driving voltage for a directional coupler modulator compared to a CPW electrode. For CPS electrodes, the transmission loss is largely determined by the transverse resonance in the substrate, while the coupling between the fundamental coplanar waveguide mode and a substrate mode affects the loss of CPW electrode [10]. This paper is aimed to provide some useful and successful methods for designing and fabricating the CPW and CPS electrodes.

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2. DESIGN CONSIDERATION

The design considerations for a high speed traveling-wave (TW) electrodes include:

(1) Near 50 Ω characteristic impedance,
(2) a low microwave electrode loss,
(3) a desired microwave effective index that matches the optical waveguide effective index, and
(4) low drive voltage.

In a practical application, it is difficult to concurrently satisfy all these requirements, some tradeoffs should be necessary.

2.1. Microwave Impedance

The electrode characteristic impedance affects both frequency response and the driving power. In order to reduce the reflections of microwaves at each end of an electrode, it is essential to have impedance matching among the electrode, drive circuit, and terminating load. It is the underlying principle of the traveling-wave electrode concept to make the electrode appear as an extension of the driving transmission line. The electrode should, therefore, have the same characteristic impedance as the driving source (50 ohm).

For traveling-wave (TW) electrodes, it has been found that the quasi-TEM approximation holds over a wide frequency range (up to 100GHz)[11,12], hence, a quasi-TEM wave transmission is assumed and employed. For the coplanar waveguide transmission line shown in Fig. 1, the characteristic impedance can be expressed as

$$Z = \frac{\sqrt{\varepsilon_{eff}}}{c}\frac{1}{C} = \frac{1}{c\sqrt{CC_0}} \tag{1}$$

$$n_{eff} = \sqrt{\varepsilon_{eff}} = \sqrt{\frac{C}{C_0}} \tag{2}$$

$$C = m\varepsilon_0(1+\varepsilon_r)K(k)/K(k') - C_P + C_t \tag{3}$$

$$C_0 = 2m\varepsilon_0 K(k)/K(k') + C_t \tag{4}$$

where C is the capacitance per unit length, and C_0 the capacitance per unit length of the structure when the substrate is replaced by air (Fig. 1); C_t is the incremental capacitance of the parallel plate capacitors formed by the side walls of the thick electrode. C_P is the reduction of total capacitance due to the polymer cladding layer(different dielectric constant) . ε_{eff} is the effective relative permittivity, n_{eff} is the effective microwave refractive index, c is the speed of light in free space. K is the complete elliptic integral of the first kind; ε_0 is the permittivity of free space, and ε_r is the relative permittivity of the optical polymer. w is width of the electrode, and g is the space between two electrodes

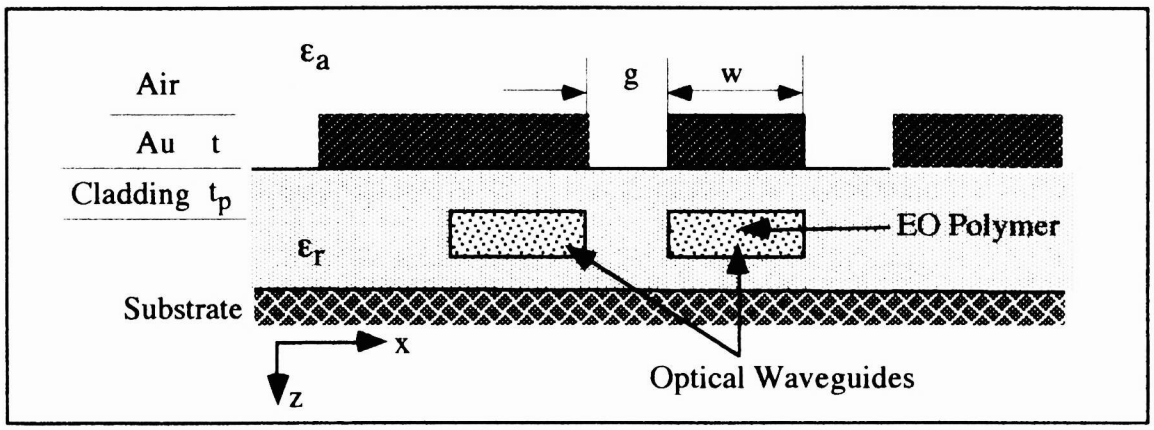

Fig. 1. Cross section of a CPW electrode for the electro-optic modulator.

For the both CPW and CPS structure, the capacitance C_t and C_p obtained from Green's function method are given by [12] as well:

$$C_t = m\pi\varepsilon_0 \frac{[a_1 - a_2 \ln(w/g) + a_3 \ln(a_4 + t/g)]}{[\ln(4g/t) + t^2/8g^2]} \quad (5)$$

For CPW, $m = 2$, a_1 = 0.49254, a_2 = 0.01709, a_3 = 0.21918, a_4 = 0.10357, and t is the electrode thickness, and ror CPS, m =1, a_1 = 0.566772, a_2 = 0.038339, a_3 = 0.224114, and a_4 = 0.088025.

For CPW:

$$C_p = 2\varepsilon_0[b_1(\Delta\varepsilon)^2 + b_2\Delta\varepsilon][1 + b_3(b_4 - k)^2]\ln(1 + b_5 t_b/g) \quad (6)$$

where $k = w/(w + 2g)$, $k' = \sqrt{1 - k^2}$, b_1 = 0.035657, b_2 = -0.886188, b_3 = -3.364278, b_4 = 0.583627, b_5 =50.9969, and $\Delta\varepsilon = (\varepsilon_{sub} - \varepsilon_r)$, ε_{sub} is the relative permittivity of the substrate.

For CPS:

$$C_p = \varepsilon_0[b_1(\Delta\varepsilon)^2 + b_2\Delta\varepsilon][1 + b_3 k]\ln(b_4 + b_5 t_b/g) \quad (7)$$

where $k = \sqrt{w/(w + g)}$, $k' = \sqrt{1 - k^2}$, b_1 = 0.152335, b_2 = -3.913483, b_3 = 0.841882, b_4 = 1.065753, and b_5 =34.3926. The accuracy of Eqs. (3) and (4) has been tested against the results obtained with the Green's function method [11-13]. The discrepancy was determined to be less than 10% . In order to get some accurate values for our devices, the coefficients will be tested by our experimental results and HP HFSS simulation.

2.2 Microwave Transmission Loss

Two factors contribute to the loss of TW electrodes: ohmic loss and dielectric loss. The ohmic loss α_c depends on the geometry of the electrode. For an electrode thickness of $t > 2d$, the electrode ohmic loss is independent of the electrode thickness being determined by the modulation frequency and the inter-electrode gap. Here d is the electrode skin depth, given by

$$d = \sqrt{1/(\pi\mu f\sigma)} \qquad (8)$$

where f is the operating frequency, μ and σ are the susceptibility and conductivity of the electrode metal, respectively. If $t < 2d$, the electrode ohmic loss is a function of electrode thickness, and increases as the electrode thickness decreases. Besides, the electrode should be made of a metal with large electrical conductivity. We have chosen pure gold (Au) over chromium (Cr) as the electrode material. The decision is backed by the superior chemical stability of gold and the existing technology of electrical gold contacts developed by the silicon VLSI industry. Electrodes can be realized by electroplating technique.

2.3 Microwave and Optical Guided Mode Phase Matching

The matching between microwave and optical mode phase is crucial to reduce the drive power for high-speed operation. One could achieve this goal by employing uniform thick traveling-wave electrodes. The bandwidth can be found by setting the position dependent phase term of the effective modulating microwave, as seen by the co-propagating light wave, equal to π [14]. This condition yields

$$f_d = \frac{c}{2N_m L}(1 - N_0/N_m)^{-1} \qquad (9)$$

where L is the interaction length of the waveguide directional coupler, and N_0 & N_m are the effective indices of the guided optical wave and the modulating microwave, respectively. The effective index N_m is a complicated function of the electrode thickness, electrode gap, cladding layer thickness and the dielectric constant of polymers employed. If the effective index N_m is much larger than N_0, short device length L has to be employed in order to obtain a required modulating speed, resulting in a large driving voltage.

Simultaneous optimization of these performance characteristics is rather complicated on account of the tradeoffs among them. The whole TW electrode is composed of several sections: active section, bends, taper, in/output. The tapers will supply both dimension and impedance matches between active section and in/output. Microwave source connects to in/output section which dimension is matched to 2.4 connector. Some simulation results are shown in Table. 1.

Section	w (um)	g (um)	t_b (um)	t (um)	Z (Ohm)	N_{eff}
Active	11	8	6	8	50.1627	1.5601
Bend	11	8	6	8	50.1627	1.5601
Taper	dependence	dependence	dependence	dependence	dependence	dependence
In/Output	220	41	6	8	50.0542	1.6562

Table.1. Detailed dimension of CPW electrode

3. FABRICATION PROCEDURE

In fabricating a thick traveling-wave electrode, various device parameters should be considered, such as the electrode dimension, thickness, inter-electrode gap, and cladding layer thickness. The detailed processing steps include:

(1) metal film deposition,
(2) micro photolithography,
(3) metal electroplating, and
(4) Ion-milling.

3.1 Metal Thin Film Deposition

A thin Cr film (300 Å) will be first deposited on the buffer layer by an E-beam evaporator. This step is important to ensure adequate adhesion of the electrode to the polymer cladding layer. Then, a thin Au film(1500~2000 Å) will be further deposited on top of the Cr , which will serve as the seed layer for electroplating thick Au electrodes.

3.2 Microphotolithography

Because the photoresist pattern is used as the guide for electroplating Au layer, the thickness of photoresist is required to be equal to the desired electrode thickness. In the practice, the thickness must be larger than designed values. Hence, a photoresist with a thickness ranging from T_l = 1.5 μm to T_u = 10 μm is necessary. Where T_l = 2d (10 GHZ) is determined by the electrode skin depth d, and T_u is depended on tradeoff among the fabrication tolerance, drive power, bandwidth, and microwave impedance match. Special photolithography techniques are required to spin-coat a thick photoresist film. The electrode pattern will be defined by an optical mask through the patterned thick photoresist layer.

3.3. Au Electroplating

Electroplating will be used to fabricate a thick gold electrode. The required electrode thickness, ranging from 1.5 μm to 10 μm, is design to get low microwave loss and a 50 Ω characteristic impedance match. In order to achieve a low loss TW electrode, the technological parameters for the electroplating procedure, including solution formula, electroplating current, and temperature, must be chosen carefully.

3.4 Ion-milling or Chemical etching

Ion-milling (reactive ion etching) will be employed to remove the Cr-Au film from inter electrode gaps. The proper etching condition will be determined for fully removing the thin Cr-Au film while not damaging the electroplated electrode.

3.5. Electrode Fabrication

The fabrication procedure is shown in Fig. 2. A polymer-based waveguide directional coupler with domain inverted sections is first fabricated. A Cr-Au film is then deposited on the cladding layer. The thick photoresist is further spin-coated on top of the thin metal film. By using standard photolithography, an electrode pattern is defined through a photo-mask. This pattern is then utilized as the electroplating guide, and a thick gold electrode is grown from the deposited Cr-Au film, being defined by the photoresist walls. The

photoresist pattern is dissolved after electroplating. Finally, the Cr-Au film is removed from the area between the electrodes by using ion-milling.

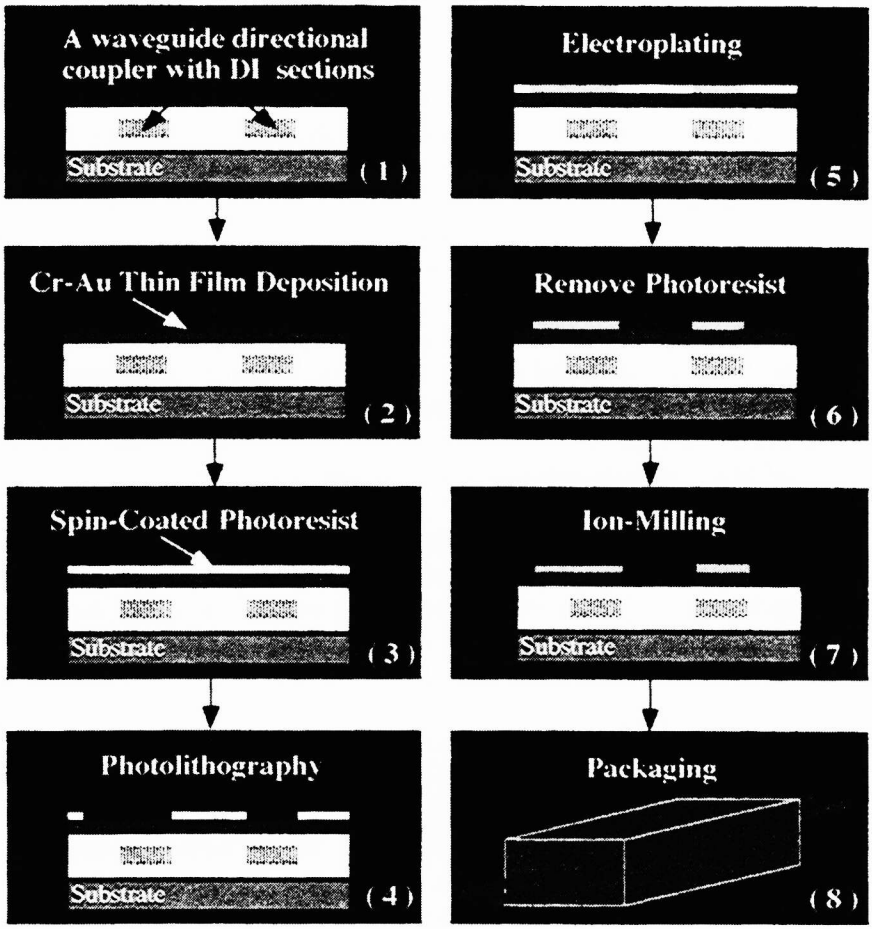

Fig. 2. Processing steps in fabricating thick electrodes.

To obtain a good thick photoresist film, AZ9200, a special high-resolution thick photoresist, was used. The photoresist thickness can be controlled by the spin speed. To ensure high-quality photoresist film, the polymer cladding should be free of contamination and excessive physically absorbed moisture. Table 2 give the detailed steps for making a 10 um thick photoresist film. The optimum spin speed (step 4) is determined by the designed thickness of photoresist film.

Step	Operation	Time (sec)	Speed (rpm)
1	Substrate Cleanin	--------	--------
2	Softbake	1800	--------
3	Spin-Coat	4-5	300
4	Spin-Coat	60	2200
5	Softbake	210	105 degree
6	Edge bead removal	10	500
7	Dry 30		1000

Table 2. Processing steps for deposition of a thick photoresist layer.

Neutral pure 24 kt gold is chosen to produce ultra pure satin bright deposition. The deposited layer can be stress free, extremely ductile and tight grained with exceptional heat and electrical conductivity. The selected electroplating solution contains no brighteners, either organic or inorganic, as well as no free cyanide or harsh alkalis and acids. Therefore, it is relatively safe and inexpensive to use. To obtain a high quality electroplated thick layer, careful preparation is essential as well.

Electroplating a thick gold electrode without uneven thickness, cracking, and lift-off is known to be difficult. This is due to the fact that there are many variables in the fabrication procedure [10], which include (1) spin-coating of EO polymers, (2) metal film deposition, (3) spin-coating thick photoresist and the photolithography of thick photoresist, (4) gold electroplating, and (5) chemical/plasma etching.

A Cr film is chosen to form the base metal for electroplating a thick gold electrode. Cr has excellent adhesion to both a polymer cladding layer and a gold film. In our experiments, a 300 Å Cr film was deposited first by an E-beam evaporator, using 100% chromium as the evaporating metal source. It has been found that thicker deposition may cause film cracking and surface roughness. In order to increase the adhesion of the gold plate and the Cr film, a thin gold film deposition was made on the top of the Cr thin film. This step was found to be necessary to avoid surface passivation of the Cr film, which prevents even plating and proper adhesion of the gold plate, resulting in an uneven thickness distribution and/or peeling.

Careful surface cleaning is required to have the exposed photoresist fully removed by the photoresist developer. It has been found that the un-removed photoresist causes severe blistering, chipping, and peeling of the plated gold electrode. Substrate dehydration is also preferred before it gets into the plating solution. It should be noted that contaminated plating solution also results in poor adhesion, poor distribution of the plate, rough plate, and cracked plates.

It has been discovered that plating conditions have significant impact on the quality of plated thick gold electrodes. The most three important factors are (1) pH value of the plating solution, (2) plating temperature, and (3) plating current density. General, the pH value for gold solution has a proper range and decrease slowly during the electroplating process. The higher pH value cause a loss of surface smoothness and can also affect plating thickness. A lower pH value cause precipitation of the gold. About temperature, we discovered that the plating temperature range from 45 to 75 degree is preferred. Lower temperatures appear to lead to poor adhesion, poor gold coverage, and brittleness. Higher temperature can result in loss of surface smoothness. Besides, the plating speed is strongly affected by the plating temperature. To minimize photoresist lift-off and solution contamination, a high plating speed(high temperature) is preferred.

The current density is an important factor in the plating process. It has been discovered that when the current density is too high, the plating solution tends to attach to the base metal (Cr/Au) too strongly. The gold in the solution is pulled to the Cr/Au so forcefully that it tends to undercut the photoresist and lift it off the wafer from the bottom. On the other hand, if the wafer is in the plating solution too long, the solution degrades the photoresist and lifts it off from the top. Since the current density is a function of the applied current and the area to be plated, the area must be carefully computed so that the correct current is applied. This is essential in determining the time for plating the desired thickness over a given part. A lower current density is applied preferably at the beginning of the plating process, until the deposited gold has built up sufficiently to prevent the undercutting. A higher current density is applied later in the plating process, to accelerate the plating process. Fig. 3 shows the photograph of the electrode masks and fabricated electrode samples.

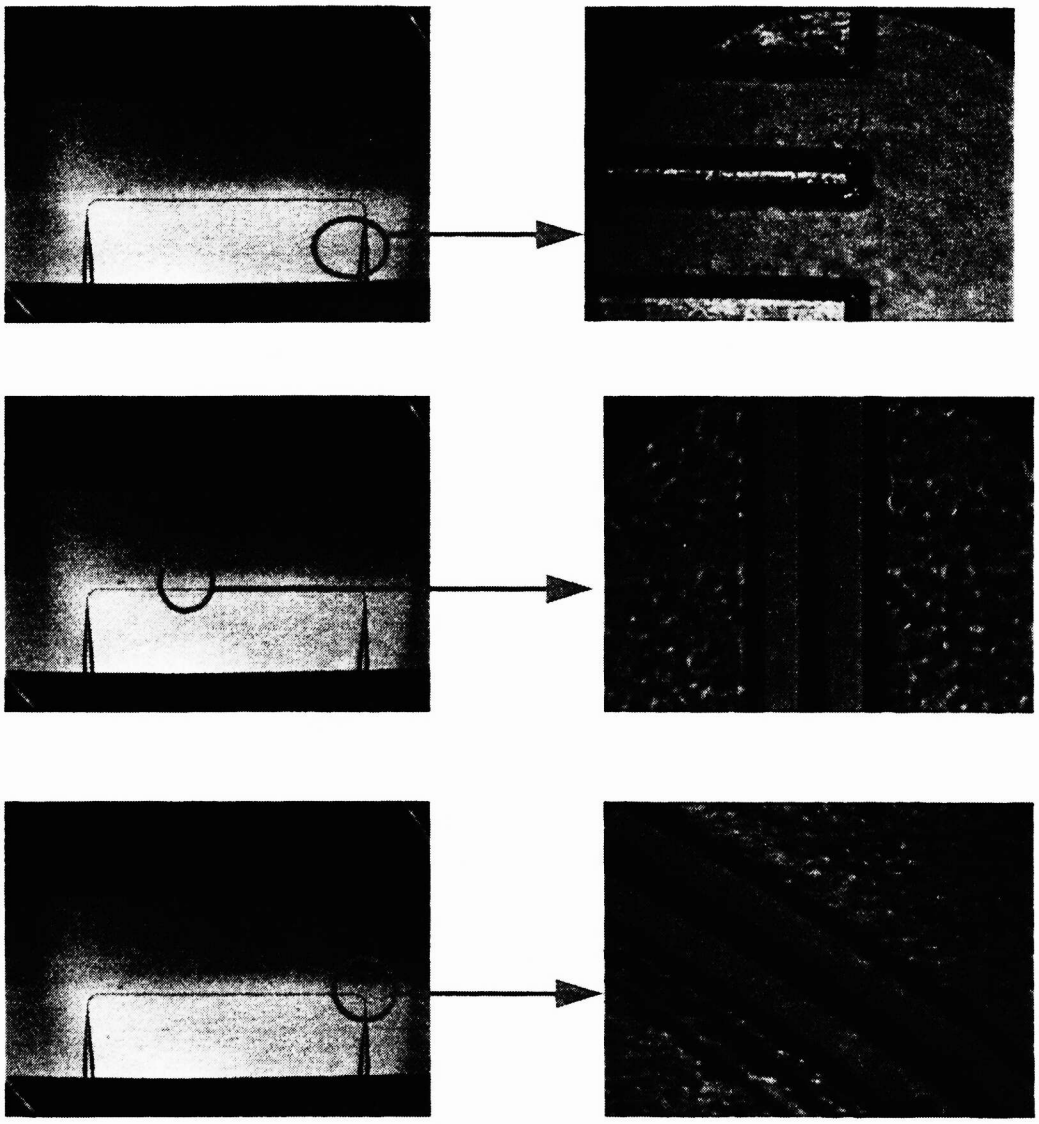

Fig. 3. Electrode mask and some samples

4. CONCLUSION

We have presented the detailed design and fabrication procedure of high-speed TW electrode. The fabrication processing steps include:(a) metal film deposition, (b) micro photolithography, (c) metal electroplating, and (d) Ion-milling. Most important factors in electrode electroplating have also emphasized and explained. Such as (1) pH value of the plating solution, (2) plating temperature, and (3) plating current density. Some electrode dimensions and good electrode samples are given as well.

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