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Sensitivity Analysis of Process Variations for Resonantly Enhanced Modulators on LiNbO₃

Thach Giang Nguyen, Yuvaraja S. Visagathilagar, *Member, IEEE*, and Arnan Mitchell, *Member, IEEE*

Abstract—A sensitivity analysis on the performance of resonantly enhanced modulators on X-cut LiNbO₃ using a thick coplanar-waveguide electrode structure due to the fabrication tolerances is presented. The distributions of the various parameters to the performance fluctuation are analyzed. It is shown that a large-gap electrode makes the modulators less sensitive to the variations of electrode dimensions.

Index Terms—Optical communication, optical modulation, resonance, sensitivity.

I. INTRODUCTION

MACH-ZEHNDER optical modulators (MZM) on LiNbO₃ have been widely used in optical-communication systems. Modulators with a very large bandwidth have been demonstrated. These modulators usually employ a traveling-wave electrode structure. In many telecommunication applications including radio-on-fiber [1], photonic oscillator [2], photonic mixing [3], optical time-division multiplexing [4], and advanced modulation format, only a narrow bandwidth is required. Thus, for these applications, the modulation efficiency over a narrow bandwidth can be enhanced using resonant electrode structures.

Recently, several resonant-type modulators have been proposed and demonstrated [5]–[7]. These modulators provide significant improvements in modulation efficiency over conventional traveling-electrode modulators. In [8], a numerical optimization technique was applied to the design of the electrode structure used in resonantly enhanced modulators on X-cut LiNbO₃. For a resonant electrode structure, the degree of the electric-field enhancement is mainly determined by the attenuation of the resonant cavity. At the same time, the inherent switching voltage of the modulator should be reduced to achieve the best possible efficiency.

The investigation in [8] suggests that optimal electrode configurations are those with thick electrodes. Thick electrodes reduce the electrode loss and the microwave propagation constant. Therefore, the degree of the resonant enhancement is increased with thick electrodes. The electrodes are usually formed by electroplating of gold on the substrate with the patterns defined by a photoresist layer. With the current elec-

troplating technology, gold electrodes with thicknesses of up to 30 μm can be realized. However, the 30- μm plating process may have somewhat large process variation. This causes a fluctuation in the characteristics of the fabricated modulator electrodes. Because of the resonant nature of the electrode, the operating frequency and the modulation efficiency of a modulator that utilizes a resonant electrode strongly depend on the characteristics of the electrode. Furthermore, due to the high-Q resonant cavity, the modulation efficiency reduces very quickly when the operating frequency moves away from the electrode resonant frequency. Therefore, to ensure high fabrication yield, it is important that the resonant frequency is relatively insensitive to fabrication variability.

In this paper, we investigate the effects of the real-world manufacturing tolerances on the performance of the resonantly enhanced modulators, including the resonant frequency and the modulation efficiency at the operating frequency. The characteristics of the fabricated modulator electrodes are calculated using FEM models, and then, the resonant performance is evaluated. In [8], it was found that although a large electrode gap makes the inherent switching voltage higher, the resonant enhancement that can be achieved with a large-gap modulator is higher than that of a narrow-gap modulator. Therefore, resonant modulators with a large electrode gap provide higher modulation efficiency at the resonant frequency than those with a smaller gap with approximately the same electrode lengths. Here, it will be shown that modulators with large electrodes are also most tolerant of the fabrication fluctuations.

II. RESONANTLY ENHANCED MODULATOR AND OPTICAL RESPONSE

By placing the terminations on both input and output ports of the modulator electrode to form a Fabry-Pérot-type cavity [9], most of the microwave signal undergoes multiple reflections inside the cavity to form resonant standing waves. This process results in an enhanced electric field inside the modulator electrode. Following [8], the terminations are simply modeled as inductors when calculating the modulator response.

The electrode of the modulator is an electroplated-gold coplanar-waveguide (CPW) structure, as shown in Fig. 1. Ti-diffused optical waveguides are formed in an X-cut and Y-propagation LiNbO₃. To minimize the coupling, the optical waveguides are separated by 26 μm . With that optical-waveguide separation, the center electrode has 22- μm width to achieve the lowest possible inherent switching voltage. The buffer-layer thickness and electrode thickness are 0.2 and 30 μm , respectively.

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Fig. 1. Modulator cross section.

With the input and output terminations attached to form the resonant cavity, the optical response of a resonantly enhanced modulator is given by Visagathilagar *et al.* [10]

$$\text{OR}(f) = \frac{\pi}{V_{\pi}L} \int_0^L V(z, f) e^{j(\frac{2\pi f}{c})n_0 z} dz \quad (1)$$

where V_{π} is the dc switching voltage of the modulator without the terminations, L is the total length of the active section, $V(z, f)$ is the complex voltage at point z along the active section of the electrode at frequency f , n_0 is the effective index of the guided optical mode, and c is the speed of light in free space.

When considering the push-pull configuration of a symmetrical modulator, the dc switching voltage can be calculated as

$$V_{\pi}L = \frac{\lambda_0 G}{n_e^3 r_{33} 2|\Gamma|} \quad (2)$$

where λ_0 is the optical wavelength in free space, G is the gap between electrodes, n_e is the extraordinary refractive index of the substrate, r_{33} is the pertinent electrooptic coefficient of LiNbO₃, and Γ is the overlap integral factor between the microwave electric field and the optical power distribution.

The optical response of a resonantly enhanced modulator has a peak at the microwave resonant frequency and quickly rolls off at other frequencies. The rate of the roll off depends on the Q-factor of the resonant cavity. For a given operating frequency f_0 and electrode configuration, the terminations and electrode length L can be optimized to achieve microwave resonance at the frequency f_0 . With fixed terminations and cavity length, the resonant frequency is largely determined by the microwave effective index of the electrode. Therefore, to keep the modulator operating at the designed frequency f_0 , the variation of the microwave effective index needs to be kept as small as possible. Any variation of the electrode cross-sectional dimensions will cause the microwave effective index, together with the characteristic impedance, attenuation constant, and the inherent switching voltage to change. This in turn causes the shift of the resonant frequency and the deviation of the modulator optical response.

III. NUMERICAL EXPERIMENTS

In the following sections, an analysis of the sensitivity of the modulator characteristics to the variations of the fabrication parameters as could be expected in a real-world manufacturing process will be presented. Two optimized modulator

electrode configurations will be considered: one with a very large electrode gap ($G = 50 \mu\text{m}$) and one with moderate gap ($G = 20 \mu\text{m}$). The designed resonant frequency is 10 GHz. The characteristics of the modulator electrode, including the microwave effective index, characteristic impedance, attenuation constant, and the inherent switching voltage for different variations of the electrode cross-sectional dimensions from their nominal values, are calculated. Then, the performance of the resulting resonantly enhanced modulators is predicted using a simulation model [10].

In order to accurately model the characteristics of thick CPW electrodes, a full wave FEM simulator [11], [12] is used. The microwave effective index, characteristic impedance, attenuation constant, and the electrooptic overlap factor Γ are then calculated from the FEM simulation.

A. Variations of the Electrode Gap and Width

In this section, the effects of the electrode gap and width variations on the performance of resonantly enhanced modulators will be investigated. The sizes of the electrode gap and width can change from the designed value due to the tolerance of the mask manufacture, photoresist development, and electroplating processes.

Fig. 2(a) and (b) shows the derivation of the microwave effective index from the nominal value when the fabricated electrode gap and width vary by $\pm 4 \mu\text{m}$ from their designed values $G-W-G = 20-22-20$ and $G-W-G = 50-22-50 \mu\text{m}$, respectively. The buffer-layer thickness and the electrode thickness are fixed at their designed values. The comparison of Fig. 2(a) and (b) reveals that in the case of the designed electrode gap of $20 \mu\text{m}$, the effective index is more sensitive to the electrode gap and width variations than the case of $50\text{-}\mu\text{m}$ designed electrode gap.

In Fig. 3(a) and (b), the contours of the variation of the peak resonant frequency, as a function of the electrode gap and width variation, are plotted. Fig. 3(a) and (b) closely resembles Fig. 2(a) and (b). In the case of the electrode with moderate gap ($G = 20 \mu\text{m}$), the peak resonant frequency can vary up to 3% from the designed frequency when the gap and width are varied by $\pm 4 \mu\text{m}$, whereas with large electrode gap ($G = 50 \mu\text{m}$), the maximum deviation of the peak resonant frequency is about 2%. It can also be seen that the peak resonant frequency does not change if the electrode gap and width vary in complimentary ways, e.g., the peak resonant frequency is maintained when the width increases by $2 \mu\text{m}$ and the gap decreases by $2.5 \mu\text{m}$ for moderate-gap configuration. This will be the case if the width and gap variations result from overetching or underetching of the photoresist-layer formation used in the electroplating process.

When the electrode gap and width change from their designed values, the electrode characteristic-impedance, attenuation, and inherent switching voltage will also change from their nominal values. These changes will cause the variations of the modulation efficiency. Fig. 4 presents the deviation of the modulator optical response from the designed value at the operating frequency. For a large gap, the impact of the variation of electrode gap and width on inherent switching voltage,

Fig. 2. Effects of G – W variations on the electrode-microwave effective index N_m . $\Delta N_m = (N_m - N_{m0})/N_{m0} * 100$, where N_{m0} is the effective index when the gap and width are at their nominal values. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

Fig. 3. Effects of G – W variations on the peak resonant frequency $\Delta f_0 = (f_r - f_0)/f_0 * 100$, where f_r is the resulting peak resonant frequency, and f_0 is the designed resonant frequency. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

Fig. 4. Effects of G – W variations on the modulator optical response. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

electrode loss, and impedance is very small [8]. However, the variation of the hot electrode width has a large effect on the inherent switching voltage. Therefore, at large electrode gap, the modulator optical response is mostly sensitive to the hot-electrode-width variation, as shown in Fig. 4(b), whereas when the gap is small, both electrode gap and width variations have an equal impact on the electrode characteristic impedance, attenuation, and inherent switching voltage. This makes the response sensitive to both gap and width variations.

It can be seen that when the fabricated hot electrode width is smaller than the designed value, the gap should be made larger in order to maintain the peak resonant frequency and the modulator response. Therefore, underetching of the photoresist pattern used for gold plating of the electrodes does not have a detrimental effect on the modulator performance. Whereas overetching of the photoresist can still provide matched resonant frequency, the modulator response is lower than the nominal value.

Fig. 5. Effects of buffer-layer-thickness and electrode-thickness variations on the electrode microwave effective index N_m . (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

Fig. 6. Effects of buffer-layer-thickness and electrode-thickness variations on the peak resonant frequency. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

B. Variations of the Buffer Layer and Electrode Thickness

The thickness of the buffer layer can be precisely controlled by the *in situ* monitoring of the layer thickness during the SiO_2 deposition process. However, when forming thick electrodes, it is difficult to accurately control the thickness of the electroplated gold layer. In this section, we investigate the effects of the variations of the buffer-layer thickness and electrode thickness on the performance of the resonantly enhanced modulators while keeping the electrode gap and width constant.

Fig. 5 shows how the microwave effective index changes with the variation of the buffer-layer thickness and electrode thickness. The microwave effective index is very sensitive to the change in the thickness of the buffer layer. However, with *in situ* monitoring, it is possible to achieve the thickness accuracy of 50 nm. As in the case of the gap and width variations of Section III-A, with a wide gap, the effective index is less sensitive to the variation of the buffer layer and electrode thickness.

The behavior of the peak resonant frequency is shown in Fig. 6 when the buffer-layer thickness varies by $\pm 0.1 \mu\text{m}$, and the electrode thickness varies by $\pm 4 \mu\text{m}$. Both wide electrode-gap and moderate electrode-gap cases are considered. When the electrode gap is $20 \mu\text{m}$, a $4\text{-}\mu\text{m}$ variation of the electrode thickness causes a 2% change of the peak resonant frequency. If

the gap is made wider to $50 \mu\text{m}$, a 1.5% change of the peak resonant frequency results from the same amount of change of the electrode thickness. The peak resonant frequency of the $50\text{-}\mu\text{m}$ nominal gap is less sensitive to the variations of the buffer-layer thickness and gold thickness than the $20\text{-}\mu\text{m}$ nominal-gap structure. However, the difference between the two structures is smaller than in the case of electrode gap and width.

In Fig. 7, the sensitivity of the modulator response at the designed frequency to the changes of the buffer-layer thickness and electrode thickness is shown. It is interesting to see that the modulator response in the $50\text{-}\mu\text{m}$ gap configuration is more sensitive to the variations of the buffer-layer thickness and electrode thickness than that in the moderate-gap modulator. It was found that the effect of the electrode-thickness variation on the inherent switching voltage is negligible [8]. Therefore, any change to the modulator response only comes from the change of the modulation enhancement due to the resonant cavity. In the small-gap configuration, the electrode-cavity loss is higher than that in the large-gap electrode. Hence, the Q-factor of the resonant cavity of the small-gap modulator is lower than that of the large-gap modulator. Therefore, the shift in the peak resonant frequency causes the modulator response to depart from the designed value more quickly in the case of the large-gap modulator.

Fig. 7. Effects of buffer-layer thickness and electrode thickness on the modulator optical response. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$.

Fig. 8. Trapezoidal CPW electrode.

Fig. 9. Variation of microwave effective index as a function of electrode wall angle.

C. Effect of Electrode Wall Angle

So far, the electrode walls have been assumed to be perfectly vertical. The optimal electrodes should have a very thick electrode to minimize the electrode loss. With the current electroplating technology, the electrode thickness of $30 \mu\text{m}$ is achievable. However, due to large thickness, the electroplating process will cause the electrode to be in trapezoidal shape, as shown in Fig. 8, with the electrode wall angle up to 10° [13], [14]. In this section, the effect of the electrode wall angle on the performance of the resonantly enhanced modulator will be considered. As in other investigations, both configurations with small and large gaps will be investigated and compared.

Fig. 9 shows the side-wall-angle dependence of the microwave effective index for both wide-gap and moderate-gap

Fig. 10. Error of peak resonant frequency as a function of electrode wall angle.

Fig. 11. Variation of modulator response at the designed frequency as a function of electrode wall angle.

electrodes. It can be seen that at a small gap, the microwave effective index varies quickly with the side-wall inclination. The degree of the effective-index variation of the large-gap electrode is much smaller. Fig. 10 shows the sensitivity to the electrode-side-wall variation of the peak resonant frequency, and Fig. 11 shows that of the modulator response at the designed frequency. At large electrode gap of $50 \mu\text{m}$, the

Fig. 12. Normalized optical response with different variations of electrode dimension and wall angle. (a) Nominal $G = 20 \mu\text{m}$ and (b) nominal $G = 50 \mu\text{m}$. The solid lines are the responses when all parameters are at their nominal values; the dashed lines are the responses when the gap is increased by $2 \mu\text{m}$, the width is increased by $2 \mu\text{m}$, the gold thickness is reduced by $4 \mu\text{m}$, the buffer-layer thickness is reduced by $0.02 \mu\text{m}$, and the electrode wall angle is -5° ; and the dotted lines are the responses when the gap is reduced by $2 \mu\text{m}$, the width is reduced by $2 \mu\text{m}$, the gold thickness is increased by $4 \mu\text{m}$, the buffer-layer thickness is increased by $0.02 \mu\text{m}$, and the electrode wall angle is 5° .

electrode can be electroplated in a single layer without any degradation to the performance. For a small electrode gap, multilayer electroplating, which is a more expensive process, may be required to keep the modulator performance within the acceptable tolerance.

D. Random Variations of Parameters

In previous sections, the effect of the variation of individual electrode dimension on the performance of the resonantly enhanced modulator has been analyzed. This section analyzes how the performance is affected if the variations in all dimensions are taken into account.

First, the worst-case scenario, in which all dimensions are varied such that the error in peak resonant frequency due to the errors in each dimension have the same sign and thus add cumulatively, producing the most extreme results, is considered. Fig. 12(a) and (b) presents the frequency-dependent optical response of these cases together with that of the nominal cases shown in for nominal gaps of 20 and 50 μm , respectively. The optical responses were normalized to the responses at 10 GHz. The results of Fig. 12(a) and (b) confirm the conclusions of the previous sections that the peak resonant frequency of the modulator with 20- μm gap departs from the designed frequency more quickly than of the 50- μm nominal-gap modulator with the same variation of electrode dimensions. It was observed in Section III-B that the modulator optical response at the designed operating frequency of the 50- μm nominal-gap modulator is more sensitive to the variation of the buffer-layer thickness and electrode thickness than that of the modulator with the 20- μm gap. However, if the variations of all electrode dimensions, are considered, the errors in the optical responses of both modulators are almost the same.

Next, a Monte Carlo analysis was performed to assess the sensitivity of the resonantly enhanced modulator with respect to random variations of electrode physical dimensions. Normal distributions were assumed for the variations of all

Fig. 13. Percentage-frequency histogram of the errors of peak resonant frequency with the random variations of electrode dimensions and wall angle.

electrode dimensions, including the electrode wall angle. The standard deviation of each dimension was electrode gap: 2 μm , width: 2 μm , gold thickness: 4 μm , buffer-layer thickness: 0.02 μm , and wall angle: 5° . The number of devices simulated was 32 000 for each case of nominal electrode gap.

The relative-frequency histograms of the errors of the peak resonant frequency for the 20- and 50- μm nominal-gap modulators are shown in Fig. 13. There are few noticeable features that can be identified from Fig. 13. As discussed previously, the variation of the peak resonant frequency of the large-gap modulator is much smaller than that of the small-gap modulator. The distributions of the peak resonant-frequency variations follow approximately normal distributions with the standard deviations of 4% and 2.4% for the 20- and 50- μm nominal-gap modulators, respectively. Out of 32 000 simulated devices, 60% of the devices with a 50- μm nominal gap have the peak resonant frequency within $\pm 2\%$ of the designed value, whereas the number for the 20- μm nominal-gap modulators is only 39%.

Fig. 14. Percentage-frequency histogram of the variations of optical response at the designed frequency with the random variations of electrode dimensions and wall angle.

Fig. 14 shows the relative-frequency histograms of the variations of the optical response at the designed frequency for both 20- and 50- μm nominal-gap modulators. Approximately 61.5% of the 32 000 simulated devices have the optical response at the designed operating frequency degrading by 3 dB or less from the designed value for both nominal-gap structures.

IV. DISCUSSIONS

In the previous sections, the effects of the variations of electrode cross-sectional dimensions and electrode wall angle on the performance of the modulators with resonant electrode structures have been analyzed. The analysis reveals that the modulator performance is less sensitive to the variations due to the fabrication process if the electrode gap is made large. With a large electrode gap, the modulators can be fabricated quickly without much penalty to the performance. It is possible, with such large structures, that low-cost fabrication techniques, such as laminated photoresists, could be used.

In these investigations, only the variations of the electrode cross-sectional dimensions have been considered. The variations of the optical-waveguide-fabrication conditions have not been investigated in this paper. The fluctuation of the optical waveguide only affects the inherent switching voltage, which leads to the overall modulation efficiency. It has no effect on the resonant behavior of the modulator; hence, a variation in optical waveguides will impact a yield in a similar manner to the broadband modulator.

V. CONCLUSION

We have presented an analysis of the sensitivity to the fabrication tolerances of resonantly enhanced modulators on X-cut LiNbO₃ with CPW-electrode structure. FEM simulation has been employed to characterize the electrodes with different variations in dimensions. The effects of the electrode wall angle were also considered. It has been shown that a large-gap electrode is a preferable choice for resonantly enhanced

modulators because modulators with a large electrode gap not only provide a better resonant enhancement but also are less sensitive to the fluctuations of the electrode cross-sectional dimensions and shape.

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