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Cascaded Multicavity Resonantly Enhanced Mach-Zehnder Modulator

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Abstract— A resonantly enhanced modulator structure with cascaded multiple resonant cavities is proposed and analyzed. The microwave effective index of the electrode can be much higher than the optical index. Therefore, the electrode structure can be optimized for high modulation efficiency and high resonant enhancement.

I. INTRODUCTION

Mach-Zehnder optical modulators (MZMs) on LiNbO₃ have been widely used in optical communication systems. Conventional modulators which employ a travelling-wave electrode structure offer very large bandwidth but low modulation efficiency. Therefore, the RF links that use MZMs suffer large link loss. In band-operation applications such as radio-on-fiber [1] and local oscillator distribution for photonic mixing [2], only a narrow bandwidth around the center frequency is required. Hence, resonant electrode structures [3], [4] can be employed in MZMs to improve the modulation efficiency at the expense of modulation bandwidth.

In order to achieve high modulation efficiency with resonant enhancement, the modulator should have low inherent switching voltage and high resonant enhancement. Resonant enhancement depends strongly on the loss of the electrode. We have practically demonstrated a highly efficient resonantly enhanced modulator (RE-MZM) on X-cut LiNbO₃ [5]. The electrode structure of this RE-MZM was numerically optimized [6] to provide low inherent switching voltage and low RF loss. However, the operating frequency was limited to less than 2 GHz. In the literature, there are several demonstration of RE-MZMs at frequencies higher than 10 GHz [4], [7]. These modulators had very high modulation enhancement with very short electrodes. Because of very short electrodes, the overall modulation efficiency of these RE-MZMs is quite low.

To increase the overall modulation efficiency, the electrode length should be made large. However, at high frequencies, in order to maintain a long electrode, the microwave effective index of the electrode must be matched to the effective index of the optical waveguide. For LiNbO₃ modulators, index matched electrodes usually have low inherent modulation efficiency and high RF loss. Furthermore, the total RF loss of a long electrode is very high. Therefore, RE-MZMs with long electrodes may not provide modulation efficiency improvement over travelling-wave modulators. To overcome the limitations

of long electrode RE-MZMs, we proposed cascaded multicavity RE-MZM [8].

This paper presents the analysis of the proposed RE-MZM structure. Particular emphasis is placed on the effectiveness of multicavity approach in improving modulation efficiency with long electrode through resonant enhancement.

II. CASCADED MULTICAVITY RE-MZM

Fig. 1. Cascaded multicavity RE-MZM structure.

In Fabry-Perot type RE-MZMs [9], the lengths of the resonant cavities are slightly less than a multiple of half of wavelength. At high frequencies, the wavelengths of the microwave signals are very short. Thus, it is possible to divide a long electrode into a number of resonant cavities [8]. Fig. 1 presents the structures of a cascaded multicavity RE-MZM. Inductive terminations are periodically added to the RF electrode to form a structure with cascaded Fabry-Perot resonant cavities. Within each cavity, strong field enhancement can be achieved provided RF loss is low. The RF power is coupled from the previous cavity into the next cavity through the inductive terminations.

In the structure of Fig. 1, the length of each resonant cavity is much shorter than the whole electrode length, therefore, the microwave effective of the electrode can be much higher than the optical index without detrimental effect to the modulation efficiency of each resonant cavity. Furthermore, the RF loss of each resonant cavity is reduced due to short length. As a consequence, the resonant enhancement factor of each cavity is improved.

With inductive terminations, the inductance of the loaded transmission line is lower than that of the unloaded electrode. Hence, the average microwave effective index of the inductively loaded electrode is lower than the effective index of the original electrode. By careful design of the inductive terminations, phase matching between the standing electric wave and the lightwave can

Fig. 2. Equivalent circuit model of a cascaded multicavity RE-MZM.

be achieved. Therefore, the constraint of index matching which usually comes with long electrode travelling-wave modulator can be removed. The electrode structure can be optimized for high inherent modulation efficiency and high resonant enhancement. In the following sections, the effectiveness of this cascaded RE-MZM structure will be investigated.

III. NUMBER OF RESONANT CAVITIES AND THE MODULATION EFFICIENCY

In this Section, the relationship between the number of resonant cavities and the performance of a cascaded multicavity RE-MZM is analyzed. Similar to [6], the inductive terminations are simply modelled as ideal inductive elements in this analysis. Fig. 2 illustrates the equivalent circuit model of a cascaded multicavity RE-MZM. For simplification of investigation, all cavities have the electrode length and all inductive terminations are identical except the first and last ones. A CPW electrode structure on X-cut LiNbO₃ is considered. As investigated in [6], the electrode has a Gap-Width-Gap configuration of 50-16-50 μm , electrode thickness of 30 μm and buffer layer thickness of 0.2 μm [6]. This electrode configuration provides the best trade-offs between the resonant enhancement and inherent switching voltage. The characteristics of the electrode obtained from a full-wave 2-D FEM simulator [10] are RF attenuation constant $\alpha_c = 0.192 \text{ dB/cm}\sqrt{\text{GHz}}$, microwave effective index $N_m = 3.086$, characteristic impedance $Z_c = 37.6 \Omega$ and inherent switching voltage length product $V_\pi L = 9.33 \text{ Vcm}$. The microwave effective index of the electrode is much higher than the effective index of the guided optical mode which is assumed to be $N_o = 2.15$. A numerical optimizer similar to the one described in [6] was employed to search for the length of each resonant cavity and inductive elements to maximize the overall modulation efficiency with a given number of cavities. An upper limit of 4 cm was imposed on the total electrode length. The optimization was conducted at a single frequency of 20 GHz. The responses of the RE-MZMs were simulated by a numerical network model [11].

Fig. 3 shows the length of each resonant cavity of RE-MZMs with different number of resonant cavities. It can be seen that the electrode length of the single cavity RE-MZM is only 4.3 mm which is much shorter than the maximum allowed length of 4 cm. This very

Fig. 3. The length of each resonant cavity of cascaded RE-MZM.

short electrode length is due to the large index mismatch between the electrode and the optical waveguide. The walk-off length of the current configuration ($N_m = 3.086$ and $N_o = 2.15$) at 20 GHz is only 8 mm which is less than twice the wavelength of the microwave signal ($\lambda_e = 4.86 \text{ mm}$). Therefore, the cavity length of the single cavity RE-MZM has to be limited to λ_e to avoid modulation efficiency penalty. However, when the electrode is periodically inductively loaded, the total electrode length can be extended well beyond the the walk-off length. Because of the total maximum length limit of 4 cm, the length of each cavity has to be reduced from around 4 mm to 2 mm which is slightly less than $\lambda_e/2$ when the number of cavity is larger than 10.

Fig. 4 shows the calculated effective V_π at 20 GHz of the resulting RE-MZM as a function of the number of resonant cavities. Since the electrooptic interaction length increases with the number of resonant cavities, increasing the number of resonant cavities improves the modulation efficiency. However, there is a sharp increase of V_π when the number of cavities increases from 10 to 11. The length of each resonant cavity of 11 cavity RE-MZM is much shorter than that of the 10 cavity RE-MZM. Hence, the 11 cavity RE-MZM has much shorter total electrode length than the 10 cavity RE-MZM. This causes V_π of 11 cavity RE-MZM higher than that of the 10 cavity RE-MZM.

Fig. 4. Effective V_π at 20 GHz of cascaded RE-MZM with different number of cavities.

IV. PERFORMANCE OF CASCADED MULTICAVITY RE-MZMs

This section analyzes the performance of the 10 cavity RE-MZM and compares that to the single cavity RE-MZM. In this investigation, the inductive terminations are represented by the shorted CPW stubs. The stubs are designed in the same LiNbO₃ substrate as the modulator electrode. The microwave characteristics of the stubs were calculated by the FEM simulator. The stub lengths were calculated from the equivalent inductive elements found in the previous section. When simulating the modulator response using the network model [11], the loss of the stubs was taken into account.

The frequency dependent effective V_π of the 10 cavity and single cavity RE-MZMs is shown in Fig. 5. It can be seen that operation at several resonant frequencies is possible. However, the peak resonant enhancement frequency is at 20 GHz. Also shown in Fig. 5 is the effective V_π calculated with the termination represented by ideal inductive elements. At 20 GHz, the V_π of the single cavity RE-MZM calculated with shorted stubs and ideal inductive terminations are very close to each other. However, the calculated V_π using the shorted stubs is 18 % higher than V_π obtained with ideal inductive terminations. This reduction of the modulation efficiency is caused by the RF loss of the stubs. The total RF loss of the stubs in the single cavity RE-MZM is small and it can be ignored. Whereas, the 10 cavity RE-MZM has a large number of stubs; hence, the RF loss due to the stubs is significant. Thus, if the terminations can be realized on a low loss microwave substrate, the degradation of modulation efficiency can be minimized.

V. CONCLUSIONS

In this paper, highly efficient resonantly enhanced optical modulators based on cascaded multicavity structure have been analyzed. It has been shown that with inductive terminations periodically added on the active electrode, the interaction length of the electrode can be made

Fig. 5. Frequency dependent effective V_π of a 10 cavity cascaded RE-MZM in comparison with that of a single cavity RE-MZM.

very large even with a large index mismatch between the RF electrode and optical waveguide. Hence, the modulation efficiency increases. Without the requirement of index matching, the electrode can be easily optimized to provide high inherent electrooptic interaction and low RF loss to achieve maximum modulation efficiency with resonant enhancement.

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