The Reduction of Harmonic and Intermodulation Distortions with a Cascaded Mach-Zehnder Modulator

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(Received March 25, 1996; Accepted July 2, 1996)

A cascaded two-stage Mach-Zehnder modulator is used to suppress the harmonic and intermodulation distortions simultaneously. The modulation electric fields are applied on the first and second stages in the y and z directions of z-cut lithium niobate crystal, respectively. Because of the inherent versatility of the adjustable modulation parameters, superior linear modulation response can be achieved. When $-50 \, \text{dB}$ nonlinear suppression is required, the modulation depth of 7.5% can be obtained.

Key words: cascaded Mach-Zehnder modulator, modulation depth, harmonic distortion, intermodulation distortion, transmission factor

1. Introduction

The external modulation of a continuous-wave laser has received increasing interest globally for high speed applications of electro-optic (EO) systems. The titanium indiffused lithium niobate (Ti:LiNbO$_3$) Mach-Zehnder modulator has found extensive applications due to its excellent EO effect. However, the linearity of the output signal is a critical problem owing to the induced Bessel-function distributions of this modulator. Several linearization techniques have been reported in the literature to reduce the nonlinear distortions, however, their reduction is primarily concentrated on the third intermodulation (IM) distortion. The dual parallel linearization system consisting of two parallel Mach-Zehnder modulators has been widely used.1-3 Because of the arrangement of the electrodes, the performance of the dual parallel modulation scheme is deteriorated by its associated crosstalk. Furthermore, a predistortion linearization technique using an additional nonlinear device to improve the distortions was also employed recently.4-6 Nevertheless, the additional electric predistortion circuit makes the system complicated and the electrical signal processing speed limits the high-frequency implementation. The John-Rousell scheme was applied to compensate for the nonlinear response by single-stage Mach-Zehnder modulator, in which the polarizations of the input optical signal were mixed with transverse electric (TE) and transverse magnetic (TM) modes.4,5,6 When the polarization angle $\theta$ is far from the $z$-axis of the LiNbO$_3$ crystal, the modulation sensitivity is degraded. The cascaded dual Mach-Zehnder modulator was proposed to reduce the third-order IM distortions but its performance was degraded by the induced higher second harmonic distortions.7 In this work, a two stage cascaded Mach-Zehnder structure is integrated in series in a LiNbO$_3$ crystal. The modulated electric fields of the first and second stages are applied in the $y$ and $z$ directions as shown in Fig. 1, respectively. Moreover, the two-tone input signals $w_1$ and $w_2$ ($w_1 \pm w_2$) are individually driven to the first and second stages. The harmonic ($2w_1, 3w_1, 2w_2, 3w_2, \ldots$) and IM ($w_1 \pm w_2, 2w_1 \pm w_2, \ldots$) distortions can be suppressed simultaneously by controlling the device operation parameters and incident laser polarization angle. The reduction of nonlinear distortions for larger frequency span can be obtained. The superior performances of the cascaded Mach-Zehnder modulator are demonstrated theoretically and experimentally.

2. Fabrication of Cascaded Mach-Zehnder Modulator

Figure 1 shows the basic configuration of the cascaded Mach-Zehnder modulator. Titanium film with a thickness of 400 Å was first deposited on the $z$-cut LiNbO$_3$ crystal. After the lift-off process, the resultant Ti pattern with a stripe width of 5 μm was diffused in a furnace at 1000°C for 6 h under dry oxygen ambient. The LiNbO$_3$ powder was used to compensate for the out-diffusion of the Li$_2$O during the diffusion period.8 Furthermore, a SiO$_2$ buffer layer with a thickness of 1000 Å was deposited and processed on the second stage region to prevent propagation loss caused by the absorption of the electrode metal. Two sets of metal Au electrodes were then deposited and lifted-off sequentially. According to the arrangement of the electrodes, the modulation electric fields of the first and second stages are applied in the $y$ and $z$ directions, respectively. The electrode gaps of the first and second stages are 24 μm and 48 μm, respectively. Length of the two sets of electrodes is 8500 μm.

3. Theoretical Analyses and Experimental Results

The experimental setup is shown in Fig. 2. The polarization angle $\theta$ of the incident He-Ne laser beam was controlled by a polarizer. The incident laser beam was focused and coupled onto the device with $20 \times$ objective lens; the output laser beam was collected by another $20 \times$ objective lens. Two tone modulation signals ($V_{1ac} \sin \omega_1 t$ and $V_{2ac} \sin \omega_2 t$) and DC biases ($V_{1dc}$ and $V_{2dc}$) were applied simultaneously to the first and second stages of the cascaded Mach-Zehnder modulator, respectively. The aperture diameter was adjusted to pass the guided beam and block the other evanescent beam. The modulated output laser beam
was then detected using a Si photodetector and shown under an oscilloscope (HP 54510A) or a spectrum analyzer (HP 8593A) sequentially.

The transmission factor is written as

\[ P_{\text{in}} = \cos^2 \theta \cos^2 (\phi_{\text{ac}} + \phi_{\text{dc}}) \cos^2 (\phi_{\text{ac}} - \phi_{\text{dc}}) \]

where \( P_{\text{in}} \) and \( P_{\text{out}} \) are the input and output intensities, respectively. \( \phi_{\text{ac}} \) and \( \phi_{\text{dc}} \) are the induced phase shifts of the \( n \)th stage due to the applied DC and AC signals, respectively. According to the configuration shown in Fig. 1, \( \phi_{\text{ac}} \) and \( \phi_{\text{dc}} \) are

\[ \phi_{\text{ac}} = \frac{\pi r_{13} V_{1,ac}}{2 V_{1}}, \]

\[ \phi_{\text{dc}} = \frac{\pi r_{22} V_{1,dc}}{2 V_{1}}, \]

\[ \phi_{\text{ac}} = \frac{\pi r_{12} V_{2,ac}}{2 V_{2}}, \]

\[ \phi_{\text{dc}} = \frac{\pi r_{33} V_{2,dc}}{2 V_{2}}, \]

where \( V_{1} \) and \( V_{2} \) are the half wave voltages of the first stage for the TE mode and second stage for the TM mode, respectively. \( r_{ij} \) and \( r_{ij}' \) are the high frequency and DC EO coefficients of the LiNbO\(_3\) crystal, respectively.\(^9\) From the measured results in this work, \( V_{1} \) and \( V_{2} \), of the first and second stages are 42 and 6.8 V, respectively. Similarly, the \( \phi_{\text{ac}} \) and \( \phi_{\text{dc}} \) can be derived and written as

\[ \phi_{\text{ac}} = \frac{\pi r_{13} V_{2,ac}}{2 V_{2}}, \]

\[ \phi_{\text{dc}} = \frac{\pi r_{22} V_{2,dc}}{2 V_{2}}, \]

Expanding Eq. (1) in terms of Bessel functions, the harmonic and IM distortions can be obtained. In this study, the second and third nonlinear distortions are considered as dominant terms and higher order nonlinear terms are neglected. We get:

the fundamental terms

\[ P_{w} = -0.5 a_1 \cos^2 \theta [J_1(X_2) + a_1 J_1(X_2) J_1(X_3)], \]

\[ P_{w} = -b_1 \sin^2 \theta J_1(X_2), \]

the second order distortions

\[ P_{2w_1} = 0.5 a_1 \cos^2 \theta [J_1(X_2) + a_1 J_1(X_2) J_1(X_3)], \]

\[ P_{2w_2} = a_1 \sin^2 \theta [J_1(X_2) + a_1 J_1(X_2) J_1(X_3)], \]

\[ P_{w_1w_2} = 0.5 b_1 \cos^2 \theta J_1(X_2) J_1(X_3). \]

the third order distortions

\[ P_{3w_1} = -0.5 b_1 \cos^2 \theta [J_1(X_2) + a_1 J_1(X_2) J_1(X_3)], \]

\[ P_{3w_2} = -b_1 \sin^2 \theta J_1(X_2), \]

\[ P_{w_1w_2w_3} = -0.5 a_1 \cos^2 \theta J_1(X_2) J_1(X_3). \]

According to Eq. (1), the transmission factor is a function of \( \theta, V_1 = (V_{1,ac} + V_{1,dc}) \) and \( V_2 = (V_{2,ac} + V_{2,dc}) \). Therefore, to obtain a large linear adjustment region, the optimum operation point can be achieved by suitable choice of \( \theta, V_{1,ac} \) and \( V_{2,ac} \). By simulating the dependences of the transmission factor on the chosen parameters simultaneously, the suitable polarization angle \( \theta \) was first set at 68°. The three dimensional curve of the transmission factor shown in Fig. 3 was then simulated. Therefore, for linear performance with larger range modulation depth operation, the simulated optimal operation point was chosen at \( \theta = 68°, V_{1,ac} = 0.25 V_{1}, \) and \( V_{2,ac} = 0.5 V_{2}. \) The applied frequencies of the first and second stages are 200 kHz \( (f_1) \) and 230 kHz \( (f_2) \) in this study, respectively. The frequencies of the second harmonic and IM distortions are 400 kHz for \( 2f_1 \), 460 kHz for \( 2f_2 \) and 430 kHz for \( f_1 + f_2 \). The frequencies of the third harmonic and IM distortions are 600 kHz for \( 3f_1 \), 600 kHz for \( 3f_2 \), 170 kHz for \( 2f_1 - f_2 \), and 630 kHz for \( 2f_2 - f_1 \). Figure 4 shows the received optical power spectrum for modulation depth 14%. The indicated frequency is from 150 kHz to 710 kHz. The span involves the frequencies of the second and third order harmonic distortion terms and IM terms. The funda-