Modulation efficiency of $LiNbO_3$ waveguide electro-optic intensity modulator operating at high microwave frequency

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Abstract

The modulation efficiency, at high frequency microwave modulation, of a $LiNbO_3$ waveguide electro-optic modulator is shown to be degraded severely especially when it is used as a frequency translator in a Brillouin distributed fibre sensing system. We derive an analytical expression for this attenuation regarding the phase velocity mismatch and the impedance mismatch during the modulation process. Theoretical results are confirmed by experimental results based on a 15Gb/s $LiNbO_3$ optical intensity modulator. OCIS codes: 060.2310, 060.2370, 060.4080, 110.4100, 190.2640

Mach-Zehnder interferometer electro-optic intensity modulators (EOMs) based on a dc voltage bias are attracting significant attention owing to their unique optical properties. A number of research groups have studied their frequency transfer characteristics, aiming especially to fabricate multiple wavelength sources [1-3]. Recently, many research groups have studied their application in distributed Brillouin fibre sensing systems, such as BOTDA and BOTDR, to convert a CW laser beam into a pulsed laser beam with the translated frequency of Brillouin shift frequency [4-6]. The attenuation of modulation efficiency was observed when the modulation frequency is at high microwave frequency in a BOTDA system, which limits its further application in the Brillouin fibre sensing system [5,6].In this work, the modulation index attenuation with respect to phase velocity mismatch and the impedance mismatch is theoretically analyzed. In addition, experiment was conducted to verify theoretical results, and modulation index from theoretical calculation and experimental results are compared.

Assuming the input optical wave of a travelling-wave EOM is $E_{in} = A\cos(\omega_0 t)$, with sinusoidal modulation $V_m \cos(\omega_m t)$ and dc bias voltage modulation V_{DC}, the output of EOM contains both upper and lower sidebands, which can be expressed in terms of Bessel functions as

$$\begin{aligned} E_{out} &= A\cos(\omega_0 t)\{J_0(C_m)\cos(\phi_{DC}+\phi_0) \\ &+ 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(C_m)\cos(\phi_{DC}+\phi_0)\cos(2n\omega_m t) \\ &+ 2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(C_m)\sin(\phi_{DC}+\phi_0)\cos[(2n-1)\omega_m t)]\} \end{aligned} \qquad (1)$$

In which $\phi_{DC} = \pi V_{DC}/V_{\pi DC}$ and $C_m = \pi V_m / V_{\pi m}$ is the modulation index of the EOM, where $V_{\pi DC}$ and $V_{\pi m}$ are half-wave voltages at RF and DC of the EOM.

Degradation of the modulation efficiency at high-frequency modulation is always found in applications of a travelling-wave EOM .The amount of modulation degradation achieved will be dependent on the modulation frequency [7-11]. Two key factors determine the modulation efficiency: (1) phase-velocity mismatch between the optical wave and the microwave, (2) impedance mismatch between the microwave source and the modulator.

Generally, the phase of the optical wave at the output end of an electro-optic crystal depends on the instantaneous electric voltage applied on the electro-optic crystal. However, when the applied frequency is high, the applied high frequency voltage will change significantly during the time the optic wave goes through the electro-optic crystal, so total phase changes during the transmission through the electro-optic crystal will be very small. The travelling microwave voltage throughout the electrode caused by the applied microwave modulation signal can be characterized by

$$V(z,t) = V_{pk}\cos[\omega_m(\frac{z}{\upsilon_m} - t)] \quad (2)$$

Where υ_m is the phase velocity of the microwave electrical signal, and V_{pk} is the peak modulation voltage.

The optical wavefront entering the input end of the electrode at time t arrives at location z at a later time of $t + z/\upsilon_o$, and υ_o is the phase velocity of the guided optical wave. It will endure a space- and time-varying voltage of $V(z, t + z/\upsilon_o)$, rather than $V(z,t)$, as it travels through the waveguide in the EOM. Therefore the electro-optically induced change in the propagation constant of the guided optical wave, as a function of modulation frequency, can be expressed as,

$$\Delta\beta(\omega, z, t) = \Delta\beta_{pk}\cos[\omega_m(\frac{z}{c}\left|\Delta n_{eff}\right| - t)] \quad (3)$$

where Δn_{eff} is the effective refractive mismatch index between the microwave and optical wave. So the phase retardation $\Delta\phi$ for the optical wave at the output end of the interferometer as a function of the modulation frequency and time can be obtained by integrating the instantaneous phase retardation over the interaction length

$$\begin{aligned}\Delta\phi(\omega,t) &= \int_0^1 \Delta\beta(\omega,z,t)dz \\ &= \frac{\Delta\phi_{pk}(0)\cos[\omega_m(t - l\Delta n_{eff}/c)]\sin[\omega_m l\Delta n_{eff}/(2c)]}{\omega_m l\Delta n_{eff}/(2c)}\end{aligned} \quad (4)$$

Where $\Delta\phi_{pk}(0)$ is the maximum phase shift induced by V_{pk} at f=0. It can be seen that a phase attenuation factor $\sin[\omega_m l\Delta n_{eff}/(2c)]/[\omega_m l\Delta n_{eff}/(2c)]$ dependent of frequency ω_m is introduced.

It is desired that the impedance of the modulator matches as closely as possible for the most efficient delivery of the microwave to the modulator, Z_L, but a perfect match is impossible and in general the impedance of the travelling-wave EOM, Z_L, changes depending on the modulation frequency. The standard impedance for the microwave source , Z_0, and the transmission line is 50 ohms. The power reflection coefficient caused by this impedance mismatch [11] can be given by $\Gamma_L = (z_L - z_0)/(z_L + z_0)$.

Figure 1 shows results of power reflection coefficient of a typical EOM. We performed a distributed measurement of the impedance and the power reflection coefficient (S11) of the EOM with a 40GHz Spectrum Analyzer (Agilent) by scanning the microwave modulation frequency from 1GHz to 15 GHz. This frequency range was chosen according to the specification of the EOM. Stars in the figure show the power reflection coefficient results obtained by calculation from measured impedances and curves in the figure show the corresponding S11.

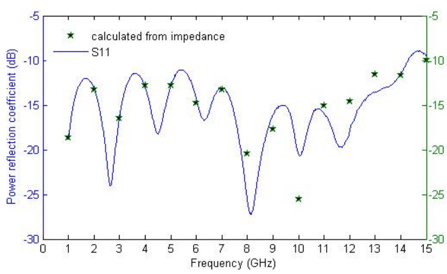

Fig.1. Power reflection coefficient vs microwave frequency

A simple experiment was conducted to provide a demonstration of this modulation attenuation. The setup for the experiment is shown in Fig.2 (a). Light from a DFB laser is coupled into an EOM (15Gb/s push-pull $LiNbO_3$ Optical Intensity Modulator) onto which a 40GHz tunable sinusoidal RF microwave source signal and dc bias voltage signal are applied. The output of the interferometer was measured using an optical spectrum analyzer (OSA) with 0.01nm resolution (AQ8384), resulting in the spectrum illustrated in Fig.2 (b).

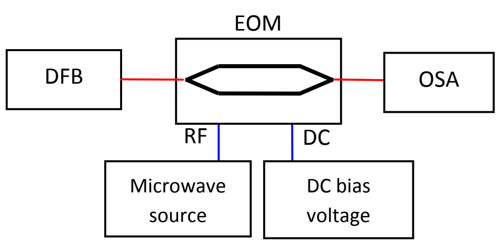

Fig.2. (a) Experiment setup for microwave modulation

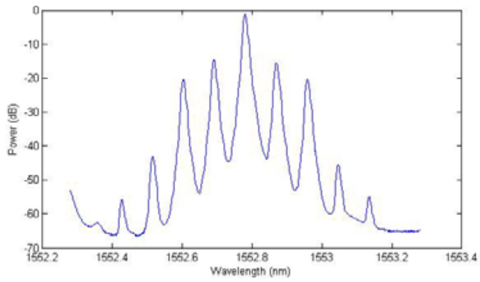

Fig.2. (b) Optical spectrum at the output of the EOM

The output spectrum depends on the dc bias voltage applied on the electrode in the EOM. In order to compare experimental results with theoretical analysis, we changed the dc bias voltage, microwave modulation amplitude, and microwave modulation frequency applied on the EOM .

The power of different harmonic wave will change periodically with dc bias voltage. Because the OSA employs a monochromator system to choose and measure input signals, this period of the harmonic wave power change will be twice that of the results we obtained from a photodetector in the low frequency shift application. The dependence of different harmonic wave power achieved from the OSA on dc bias voltage was experimentally investigated, as shown in Fig.3. It can be seen that peaks of odd order harmonic wave occur at 6.5 V, and peaks of even order harmonics wave are at 1V and 11V. This is in good agreement with the measurement principle of the OSA.

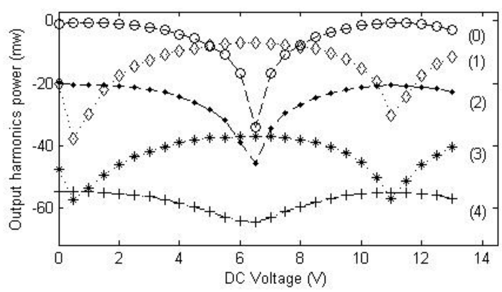

Fig.3. Power dependent of the measured output harmonics

where (0) $P_{\omega0}$, (1) $P_{\omega0+\omega m}$, (2) $P_{\omega0+2\omega m}$, (3) $P_{\omega0+3\omega m}$, (4) $P_{\omega0+4\omega m}$

The modulation efficiency (modulation index C_m) was determined by measuring the power in the carrier and different harmonic wave at different dc bias voltages to the EOM, using

$$\frac{P_{\omega_0+\omega_m}}{P_{\omega_0+3\omega_m}} = \frac{J_1^2(C_m)}{J_3^2(C_m)}, \frac{P_{\omega_0+2\omega_m}}{P_{\omega_0+4\omega_m}} = \frac{J_2^2(C_m)}{J_4^2(C_m)} \qquad (5)$$

Fig.4 shows modulation results when microwave modulation powers of 26dBm and 20dBm were applied on the EOM separately. The expected modulation index, C_m, without any attenuation should be 1.708 and 0.9032 respectively, which are also shown in the figure. The lower curve at 20dBm is calculated from $P_{\omega0+\omega m}$ and $P_{\omega0+3\omega m}$measured at 6.5V dc bias voltage. There are three curves in the upper curve cluster, and they are in agreement with each other. Star points are calculated from $P_{\omega0+2\omega m}$ and $P_{\omega0+4\omega m}$ measured at 1.8V dc bias voltage, crosses are from $P_{\omega0}$ and $P_{\omega0+2\omega m}$ at 1.8V, and solid circles come from $P_{\omega0+\omega m}$ and $P_{\omega0+3\omega m}$ at 6.5V. This proves the only and significant dependence of attenuation of modulation index on frequency.

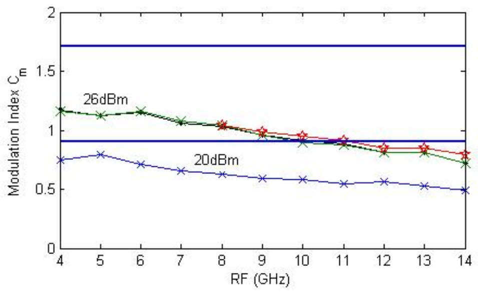

Fig.4. Experimental results of modulation index C_m against RF

Finally, the C_m has been calculated theoretically, considering the phase velocity mismatch and impedance mismatch analyzed above. Corresponding results are shown inFig.5 with experimental results. The upper flat line shows the expected C_m, regardless of any attenuation. Discrete star points show experimental results. Three curves show theoretical results with different Δn_{eff} (from 0.13 to 0.2), and the value of Δn_{eff} is from 0.18 to 0.2 according to the EOM provider, but it seems to be 0.13 from our tests. The range from 0.13 to 0.2 is within our tolerance, for it can be as high as 2.08 in EOMs. Experimental results and theoretical ones are in agreement with each other.

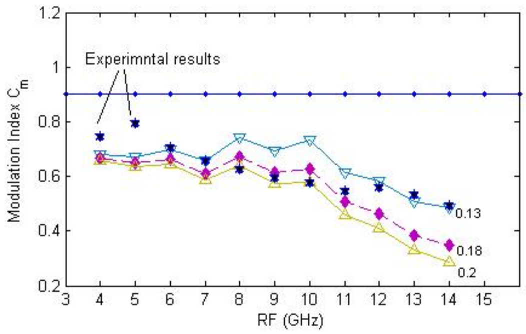

Fig.5. Comparison of modulation index C_m from calculation and experiment

In conclusion, the attenuation of modulation efficiency of a $LiNbO_3$ Optical Intensity Modulator, modulated at high frequency into microwave region has been studied. Two main factors, the phase retardation over the interaction length and the power reflection from impedance mismatch, were proposed to verify this attenuation. Experimental results confirmed this frequency related power reflection and modulation efficiency degradation, and are in good agreement with analyzed results.

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