Novel Design for the Broadband Linearized Optical Intensity Modulator

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ABSTRACT

The field of microwave photonics in which the radio-frequency signal is transmitted using an optical link has been experiencing rapid growth in the last decade. There is a demand for compact, robust and inexpensive devices capable of achieving high fidelity analog transmission between two remote locations. Analog transmission possesses an inherent advantage of being transparent to various modulation formats in many bands. Many applications require large dynamic range (over 130dB/Hz) and large (few GHz) bandwidth. In such applications the element limiting the performance turns out to be the optical intensity modulator. The typical intensity modulator based on the Mach-Zehnder interferometer (MZI) has a nonlinear response and thus exhibits strong third-order intermodulation distortion limiting the dynamic range. Numerous suggestions for linearization of the MZI response [1-5] have not become practical due to their complexity of design.

We propose a novel, exceptionally simple way of linearization of the intensity modulator response based on combining a MZI and a low-Q off-resonant Gires-Tornois interferometer (GTI) in one integrated package. In this design the third-order intermodulation distortion can be completely cancelled raising the spur-free dynamic range to 130dB in 1Hz bandwidth. At the same time, due to the low Q of the GTI a bandwidth in excess of 3GHz can be attained anywhere in a 0-45GHz range.

INTRODUCTION

The rapid growth in both military and civilian applications of microwave technology, including radar, communications, remote sensing, etc. has resulted in the increase of both the speed and complexity of transmitters and receivers. Examples include phased array antennas consisting of multiple transmitters and receivers. An attractive solution to the speed and complexity problem is to transform the microwave signal into the optical domain, perform as many processing and transmitting functions in the optical domain as possible, with low loss and interference and then go back to the electrical domain. The efficient method to impose the analog signal onto the optical carrier is the usage of an external electro-optical modulator (EOM) based on the Pockels effect, since other methods suffer from excessive insertion loss and residual frequency chirp.

A typical EOM consists of an interferometer in which one or both arms include an electro-optic element. The interferometer shown in Fig.1 is a Mach-Zehnder interferometer (MZI) [1,2] but other schemes can be used, such as a Michelson Interferometer.

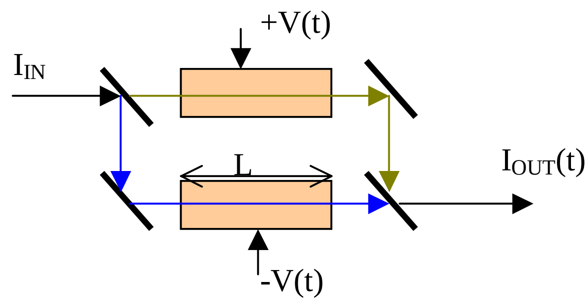

Figure 1. The principal scheme of an EOM based on the MZ interferometer

EOM's based on interferometric schemes had been spectacularly successful in the digital domain, however, when it comes to analog modulating schemes used in radars, sensors and CATV these EOM's suffer from an important drawback. Their response is not linear but rather sinusoidal:

$$I_{OUT}(t) = \frac{1}{2} I_{IN} \left[1 + \sin[2 n_0^3 \pi f_o L d^{-1} c^{-1} V(t)] \right] \qquad (1),$$

where d is the effective distance over which the voltage is applied, f_0 is the optical frequency, c is the speed of light in a vacuum, L is the length of the electro-optic elements, V(t) is a time-varying input voltage signal, n_o is the index of refraction of the electro-optical medium, I_{IN} is the input laser power and $I_{OUT}(t)$ is the output optical signal. As a result, when the input voltage increases, the output signal becomes distorted. If the input signal contains different modulation frequencies, F_{m1} and F_{m2} then the output signal will contain the spurious intermodulation sidebands, $2F_{m1} - F_{m2}$ and $2F_{m2} - F_{m1}$. The intensity of

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the intermodulation sidebands grows with the increase in input signal, and eventually becomes comparable to the signal itself. The output intensity at which this takes place is called the IP_3 point, and it is the difference (in dB) between the IP_3 and the noise floor that determines the so-called spur-free dynamic range (SFDR) of the system. Clearly, the SFDR of the link is limited by the nonlinearity of the EOM and one should look for ways to mitigate this.

Indeed, there have been numerous proposals made to improve the modulation linearity. Among them is the dual-polarization technique [3], the paralleled MZI scheme [4] and the cascaded MZI scheme [5,6]. None of these schemes have found a practical application, mostly due to implementation difficulties since precise control of the lengths and voltages on multiple electrodes is required. Alternatively, the linearization can be performed in the electronic domain, by super-linearly pre-distorting the EOM driving voltage [7], but that method demands high-speed nonlinear electronic devices, which are not readily available for fast modulation frequencies.

Our approach is based on a novel kind of electro-optic modulators namely the EOM as a combination of two consecutive interferometers with inverse non-linear characteristics that cancel each other. The third-order nonlinear distortion is completely cancelled optically.

TECHNICAL APPROACH

In this section we investigate the inherent nonlinearity of the EOM, shown in Fig.1. The output intensity of the quadrature point biased MZI is described by (1). The plot of function (1) is shown in Fig.2 (a). The MZI and its variations such as the Michelson interferometer are essentially a phase-to-amplitude converters, converting the variations in the phase difference between their two arms, $\Phi_1 - \Phi_2$, into intensity variations according to (1):

$$I_{out}(t) = \frac{1}{2} I_{in} + \frac{1}{2} I_{in} \sin(\Phi_1 - \Phi_2) \sim \qquad (2)$$

$$\sim \frac{1}{2} I_{in} + \frac{1}{2} I_{in} (\Phi_1 - \Phi_2) - \frac{1}{12} I_{in} (\Phi_1 - \Phi_2)^3 + ...$$

This response is sinusoidal, i.e**. sub-linear**. Therefore, for as long as the phase difference $\Phi_1 - \Phi_2$ remains a **linear** function of the applied voltage V(t) in accordance with (1), the overall characteristic I_{OUT} vs. V shown in Fig.2(a) stays **sub-linear.**

Clearly, in order to linearize the modulator it is necessary to utilize a pair of phase modulating elements in its arms

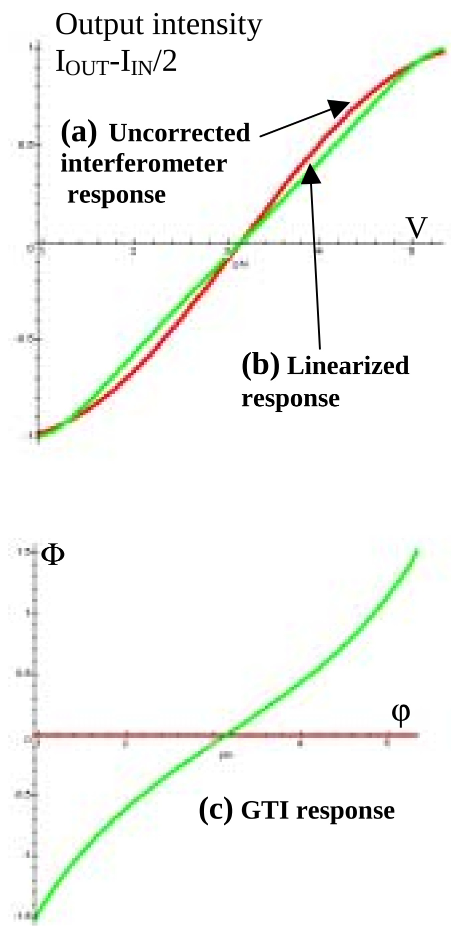

Figure 2. Intensity output of the Michelson interferometer vs. applied voltage: (a) uncorrected interferometer, (b) interferometer with GTI's in its arms, (c) Phase delay Φ of the reflected ray vs the round trip phase delay ϕ of the GTI.

that have a **super-linear (inverse to sub-linear)** dependence of the phase difference $\Phi_1 - \Phi_2$ on voltage.

We propose to use a rather simple and well-known optical element – the Gires-Tornouis interferometer (GTI) to cancel the largest, third order, nonlinearity.

A typical GTI , shown in Fig.3,a is essentially a Fabri-Perot interferometer with the rear mirror having 100% reflectivity and the front mirror reflectivity of r^2. We propose to use an active GTI made of an electro-optic material with transverse applied voltage (Fig.3, b). This scheme has the crucial advantage of lower voltage, especially if implemented in the waveguide geometry.

When one works with the GTI it is important to differentiate between the phase delay accumulated by the light during one round trip in the cavity

$\varphi = 4\pi f_0 n(V) L c^{-1}$ and the total phase delay Φ experienced by the beam reflected from the GTI. The amplitude of the reflected beam is equal to the amplitude of the incident beam as long as there are no losses in the GTI, while the phase shift is

$$\Phi = \tan^{-1} \frac{(1-r^2)\sin\varphi}{(1+r^2)\cos\varphi - 2r} \qquad (3).$$

This function is plotted in Fig.2 (c) for r^2~12%. Clearly the curve is super-linear in the vicinity of $\varphi = \pi$. Therefore with the proper bias, one obtains a **super-linear** dependence of the GTI

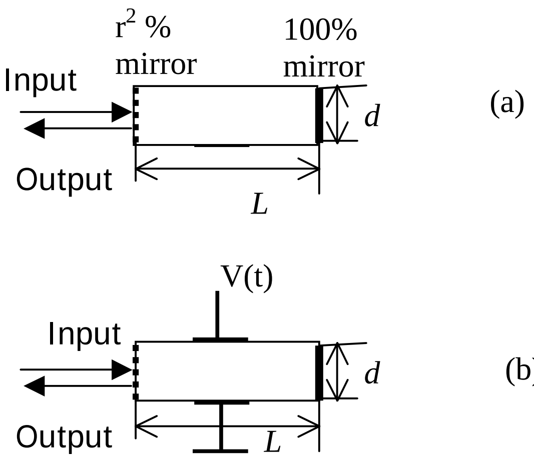

Figure 3. Gires-Tornois interferometer: (a) passive, (b) active.

phase shift on the applied voltage V(t), and it can compensate for the sub-linearity of the interferometer itself. In Fig. 4 we show the modulator that consists of two GTIs driven with V(t) and –V(t) respectively, inserted into two arms of a Michelson interferometer. The total intensity response of the modulator is:

$$P_{OUT} = P_{IN}\left[1 + \sin 2\tan^{-1}\frac{(1-r^2)\sin 2\pi f_0 n_0^3 r V(t) L/(dc)}{(1+r^2)\cos 2\pi f_0 n_0^3 r V(t) L/(dc) + 2r}\right] \quad (4).$$

This response is shown in Fig.2 (curve b). (The uncorrected response of the interferometric modulator (Eq.3) is also shown (curve a.)). One can clearly see the improvement offered by the linearization. Detailed analysis shows that one can reduce the undesirable intermodulation in this device by more than 10dB, thus the spur-free dynamic range can be increased accordingly. Our conservative estimate predicts that with 10dBm laser power, 3GHz bandwidth and 4dB noise we can obtain a 12dB improvement in SFDR, from 44dB to 56dB, compared with traditional MZI modulator. This translates into 132dB in 1Hz vs. 110dB in 1Hz for the uncorrected scheme (MZI). Further improvement can be achieved by designing asymmetric GTI's to cancel the fifth order distortion.

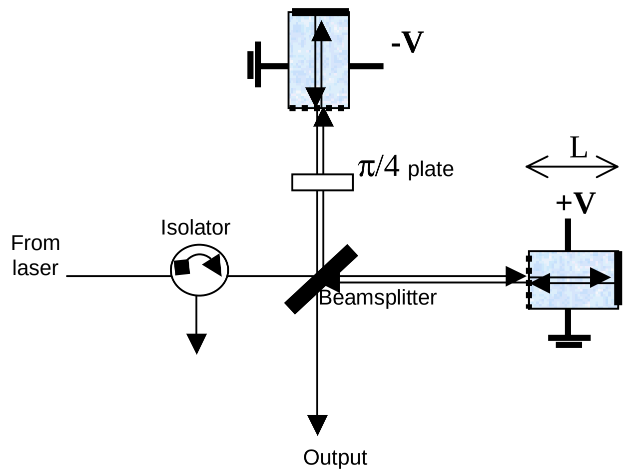

Figure 4. Michelson Interferometer with electro-optic GTIs in its arms.

The improvement of the dynamic range should not come at the expense of the other important characteristics of the EOM: driving voltage and speed. The driving voltage required to achieve a maximum swing of the output power is approximately

$V_{\max} \sim V_{\pi/2} \sim \frac{d}{4L}\frac{c}{f_0}\frac{1}{n_o^3 r} \sim 2\frac{d}{L}\times 10^3 V$, where we have assumed that we use transverse geometry with X-cut $LiNbO_3$ $(r = 30\,pm/V, n_0 = 2.2)$ and wavelength of 1500nm. When it comes to the maximum operating frequency, $F_{\max}$, it is primarily determined by the round trip time through the GTI: $F_{\max} = c/4n_0 L \sim 3GHz/L(cm)$. It is important to stress here that since the GTI in our scheme operates far away from the resonance condition ($\varphi = \pi$), and its Q-factor is low, it is not subjected to the severe bandwidth limitations characteristic of Fabri-Perot modulators operating at resonance ($\varphi = 2\pi$). Thus a GHz scale bandwidth can be attained. In order to shift the center frequency from 0 to some other frequency, one needs to use a traveling wave arrangement.

LINEARIZED INTENSITY MODULATOR OPERATING AT UP TO 10 GHZ.

In order to increase the speed of the EOM we need to use a rather short device, but this requires higher electric field. Higher electric fields can be achieved via waveguide geometry (Fig.5).

The proposed device is designed for Lithium Niobate planar waveguide manufacturing process that can be done on a single wafer or on two wafers. The first part is a Michelson interferometer which is essentially a 50/50 directional coupler whose splitting ratio can be adjusted with the electrical field (applied voltage V_1). The second part is essentially two GTIs, i.e. two waveguide EOM with two mirrors (deposited gold layer). The rear mirror is highly reflective (~100%) and the front mirror is partially reflective. There are also two additional "push-pull" biasing electrodes for error compensation and operation point (dynamic) adjustment (applied voltage V_2, V_3). These two parts can be made on one wafer and separated by a groove (saw cut filled with epoxy with matching refractive index) as shown in Fig.5. Another approach is to make the two parts on one wafer, cut them completely and then bond them together using epoxy. This is a unique high risk technology. The advantage of the proposed monolithic design is the high integration level of the electro-optical components within a single $LiNbO_3$ crystal die. The critical elements of this device are the fabrication of semi-transparent coatings with high precision.

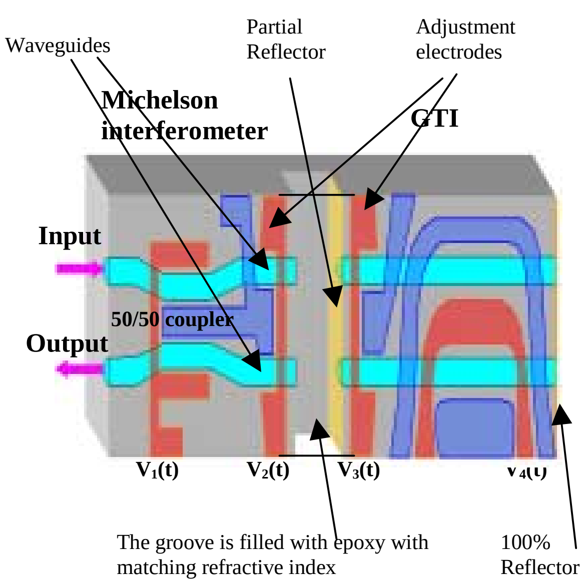

Figure 5. Waveguide implementation of the linearized modulator

The device is designed for a 3" $LiNbO_3$ wafer, using Titanium in-diffused technology. The waveguides are designed for single-mode TE operation on X-cut, Y-propagation crystal. The substrate is coated with a buffer layer of silicon dioxide (SiO_2). The waveguide EOM employs a thick plated gold coplanar-waveguide (CPW) traveling-wave type electrode structure (applied voltage V_4), which is formed on the buffer layer. The SiO_2 and gold thickness could be optimized for velocity matching of the optical and electrical signals. The waveguide EOM is driven by RF signals applied to the on-chip CPWs.

The CPW is designed for 50 Ohms impedance. The lengths of the RF electrodes are functions of the required operating voltage and frequency. This integrated modulator package is designed for tens of Giga symbol/s amplitude shift keying modulation. The device can be optimized for 10GHz operation by the proper choice of the round trip time.

The separating groove can be achieved by using "*integrated knife-grooves*". This unique technology, based on the very precise dicing and/or coating of $LiNbO_3$ crystal, was specially developed to introduce low insertion loss coupling into $LiNbO_3$ integrated structures. By means of this technique the complicated free-space alignment procedure can be avoided enabling the direct mirrors deposition of the crystal edge. The undesirable reflections from the non-reflective edge can be minimized by appropriate antireflection coating or an angled cut.

SUMMARY

The novelty of our **linearized intensity modulator**

- Combines the superlinear characteristic of Gires-Tornois Interferometer with the sublinear characteristic of Michelson interferometer to cancel the third-order nonlinearity.

Its salient features:

- The approach is all optical and works at operating frequencies of up to 40GHz
- The bandwidth is 3GHz and up
- Spur-free-dynamic range is over 130dB/Hz
- It is integrated using $LiNbO_3$ technology into one small-size rugged package
- More than one linearized intensity modulator can be integrated on one substrate
- There are no free-space optical components
- The modulator includes automatic adjustment for the temperature and thus does not require cooling.

A linear optical modulator is an enabling component for compact, robust and inexpensive devices capable of achieving high fidelity analog transmission between two remote locations. The efficient using of bandwidth, reasonable electronic operating speed and power consumptions make it very attractive for various military applications including battlefield. This technology is also crucial for civilian applications in microwave technology, including radar, communications, remote sensing, etc.

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