Effects of amplitude modulation and non-linearity in phase modulators on a unidirectional phase modulator

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A unidirectional phase modulator consisting of two phase modulators is studied experimentally. Analysis of the results shows the importance of non-linear and residual amplitude modulation effects in the modulators.

Introduction

Isolators play a key role in many applications of optics. Unfortunately it has proven difficult to integrate optical isolators based on the Faraday effect into a Photonic Integrated Circuit, motivating the search for other types of isolators that are more easily integrated.

One of such isolators consists of two electro-refractive modulators (ERMs) and a spectral filter [1] and is schematically represented in Fig. 1. The modulators are both driven by a sinusoidal RF signal of frequency f, but a phase difference ϕ exists between the two. The modulators are spaced by a specific distance L. While the light is travelling from one modulator to the next, the electrical signals will accumulate $2\pi f L/v_g$ radians of phase. Because of the phase difference between the two modulators, symmetry of the device is broken and the tandem of phase modulators becomes a direction dependent device. The tandem of ERMs can conceptually be replaced by a single ERM with an effective modulation amplitude that is dependent on the propagation direction of the light. By proper design, phase modulation only occurs for light propagating in the backward direction while light propagating in the forward direction is unaffected. Therefore we shall refer to the tandem of modulators as a unidirectional phase modulator (UPM). Isolation can be achieved by placing a bandpass filter at the input of the UPM to attenuate the sidebands generated by the UPM.

This work studies the UPM in more detail with the aim of predicting its behaviour when it is integrated into the cavity of a ring laser. First we present the model we use to describe the behaviour of the UPM, then the setup for characterization is explained and finally the characterization results are presented and conclusions are drawn.

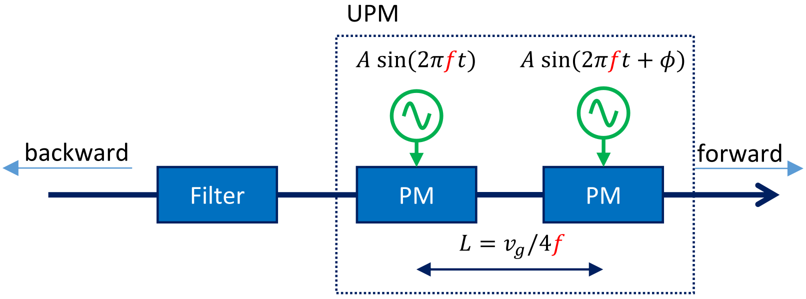


Figure 1: Schematic overview of an isolator based on a unidirectional phase modulator consisting of two ERMs driven by sinusoidal electrical signals. Both modulators are driven at frequency f, with phase difference ϕ. The modulators are spaced by a distance L. v_g denotes the group velocity of waveguide between the two modulators.

UPM model

The ERMs ideally modulate the phase of the light linearly with voltage. It is however well known that these modulators are non-linear and that they impose some residual amplitude modulation (RAM) on the light passing through them. We assume that the effect of a single modulator is of the form

$$\Delta n(\tau) = A(1 - i\gamma)[\sin(2\pi f\tau + \phi) + \beta \sin^2(2\pi f\tau + \phi)], \qquad (1)$$

where $\Delta n(\tau)$ is the average group index in the ERM at time τ, A is the modulation amplitude, γ is the RAM relative to the phase modulation, β characterizes the non-linearity of the modulator and ϕ is the phase of the electrical signal driving the modulator. Note that both phase- and amplitude modulation are accounted for up to second order and that they are assumed to scale linearly with the first order modulation of the refractive index. The values of A, β and γ will later be obtained from a fit of the measurement data.

To obtain a model for the UPM, we realize that it consists of two ERMs with a direction dependent phase difference, $\Delta\phi_\pm$. Here the $+$ denotes propagation in the forward direction and – denotes propagation in the backwards direction. We number the ERMs in the UPM 1 and 2 and denote their parameters as in (1) with an added subscript. We assume that both modulators are sufficiently identical, leading to $\gamma_1 = \gamma_2 = \gamma$ and $\beta_1 = \beta_2 = \beta$. The electrical signals are not assumed to be identical. This allows for different electrical paths for the driving signals. We define $\alpha \equiv A_1/A_2$. Finally, we realize the electrical signal accumulates $2\pi f L/v_g$ radians of phase while the light is propagating from one ERM to the next. This results in $\Delta\phi_\pm = \phi_2 - \phi_1 \pm 2\pi f L/v_g$.

The effect on the phase of the light is modeled by the transmission of the UPM, $t = \exp\left(i2\pi L \frac{\Delta n}{\lambda}\right)$. After some manipulation this can be written as

$$t = \sum_{m=-\infty}^{\infty} \exp(i2\pi m f t) \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_j\left(-\frac{\alpha\beta X}{2}\right) J_k\left(-\frac{\beta X}{2}\right) J_l(\alpha X) J_{m-2j-2k-l}(X) \exp(i\theta) \qquad (3a)$$

where J_j is the Bessel function of the first kind, j-th order and

$$\theta \equiv \left(\frac{(1+\alpha)\beta X}{2} + \frac{\pi}{2}(j+k) + \Delta\phi_\pm(2j+l)\right) \qquad \text{and} \qquad X \equiv \frac{2\pi L A(1-i\gamma)}{\lambda}. \qquad (3b)$$

From (3a) it can be seen that the UPM will transmit a comb of frequencies, centered at the optical frequency of the input light and with a comb spacing equal to the electrical frequency of the signals driving the modulators, just as is the case for a single phase modulator. When the UPM is perfect, i.e. $\alpha = 1$, $\beta = 0$ and $\gamma = 0$, (2) becomes the exponent of a sum of sinusoids and can be written as

$$t = \sum_{m=-\infty}^{\infty} \exp(i2\pi m f\tau)\ J_m\left(\frac{2\pi L}{\lambda} A\sqrt{2 + 2\cos\Delta\phi_\pm}\right) \exp\left(im \operatorname{atan}\left(\frac{\sin\Delta\phi_\pm}{1+\cos\Delta\phi_\pm}\right)\right). \qquad (4)$$

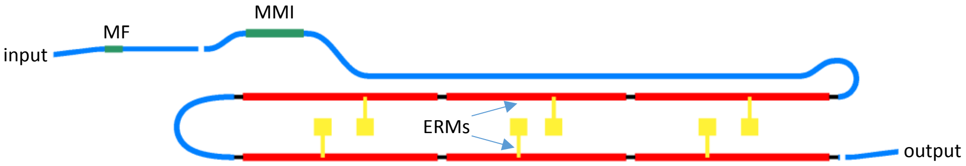


Figure 2: Schematic representation of UPM layout. The UPM consists of the six ERMs in the bottom, of which only the two that are indicated are used. On the left light passes through a mode filter, a 2x2-MMI and a length of deeply etched waveguide before it enters the UPM. The other two waveguides connecting to the MMI are not shown. On the right, the light is directly coupled to a lensed fiber.

For this ideal case (4) implies that there is no modulation in the forward direction, while the light propagating in the backward direction is modulated with amplitude $4\pi LA/\lambda$ as $\Delta\phi_+ = \pi$ and $\Delta\phi_- = 0$ for these ideal parameters.

Experiment

In order to test the model, a UPM was fabricated in SMART multi-project wafer run 14 (SP14). The layout of the UPM is schematically presented in Fig. 2. The UPM was wire bonded to a PCB, to which a bias-T was connected. Both ERMs were biased at -6V and an RF signal of 3.5GHz was applied to both ERMs. The RF amplitudes were set to V_1 and V_2 respectively. Lensed fibers were aligned to both ends of the UPM and a continuous wave laser set at 1550nm and 10mW was used to illuminate the structure from the left. At the other side the optical spectrum was characterized using an optical spectrum analyzer (OSA) with 20MHz resolution.

For an amplitude of 20dBm and a set phase difference of 0 degrees, this resulted in the spectrum presented in Fig. 3. From this spectrum we calculated the relative power in the generated peaks and numbered the peaks as shown in the same figure. We then performed a sweep of the phase difference between the two RF signals driving the ERMs for various amplitude unbalances. In this way Fig. 4 was obtained. The solid lines in this figure are drawn for $A = 0.46$ rad, $\alpha = 1.17\,V_1/V_2$, $\beta = 0.058$, $\gamma = 0.1$. In an ideal system it would be expected that $\alpha = A_1/A_2$. The deviation from this value is likely caused by a difference in transmission of the RF signal and a difference between the modulation efficiency of the ERMs.

Fig. 4 shows that the second order peaks are present for all RF phase differences. In practice this means that the UPM will modulate some of the light propagating in the forward direction. The first order peaks can be completely suppressed for the forward propagating wave when $\alpha = 1$. Finally, it can be seen that only about 2.2dB suppression of the zeroth order peak was achieved, which translates to the same amount of isolation when the UPM is combined with a perfect filter. Since $A = 0.46$ rad as opposed to the ideal 1.2 rad, we attribute this to

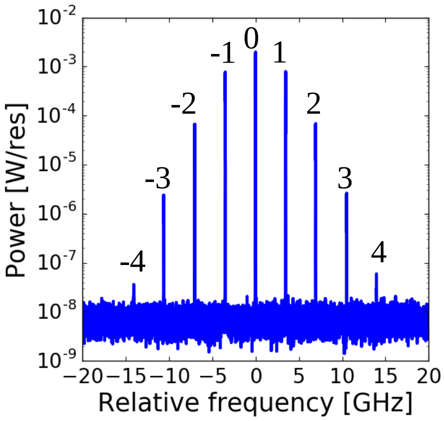
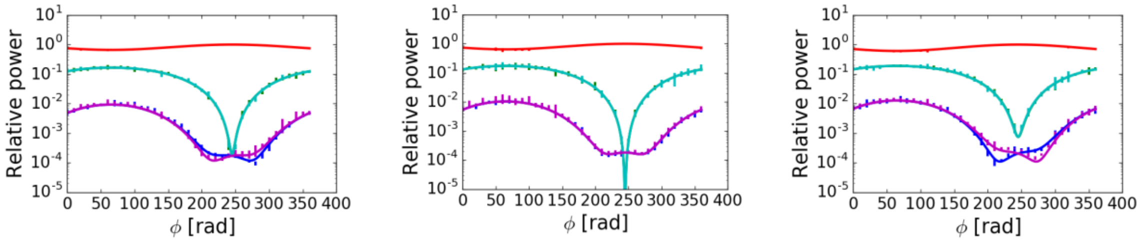


Figure 3: Transmitted spectrum for modulation amplitude of 20dBm and 0 phase difference. The frequency is relative to the frequency with the highest peak and the numbers indicate the numbering of the peaks used. The ERMs were biased at -6V.



(a) $V_1 = 2.53V$ (b) $V_1 = 2.69V$ (c) $V_1 = 3.0V$

Figure 4: Power in generated peaks as a function of phase difference between the RF driving signals V_1 and V_2. Blue, green, red, cyan and purple indicate peaks -2, -1, 0, 1 and 2 respectively. The bars indicate a standard deviation of five measurements, while the solid line indicates the fitted model. V_2 =3.0V for all subfigures, while V_1 was varied.

an insufficient modulation amplitude. This is likely caused by an inefficient design of the electrical path between the signal generators and the ERMs that includes a sub-optimal PCB and long bond-wires. If we assume the modulation amplitudes can be increased to their optimal values, we obtain the graph presented in Fig. 5. Here it can be seen that the second order modulation effects are still present on the forward propagating wave. It also shows a predicted maximum isolation of more than 20dB.

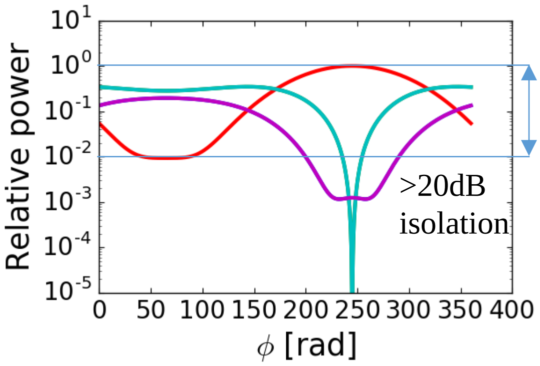


Figure 5: Predicted power in the generated peaks for the optimal electrical input. Colors as in Fig. 4. Note that the purple and blue line, and the green and cyan lines overlap indicating a symmetric spectrum.

Conclusion

The unidirectional phase modulator proposed in [1] was studied in more detail. A model for the component was created and verified experimentally. The model was found to show good agreement with the experimental data. The second order modulation amplitude was found to be approximately 5.8% of the linear modulation amplitude and residual amplitude modulation was found to be around 10% of the phase modulation amplitude. These values are properties of the ERMs and possibly the electrical signal path and are therefore not easily changed. A prediction for optimal modulation was made, which yields a predicted behavior shown in Fig. 5. Together with a suitable filter and when properly driven, this UPM is predicted to allow for 20dB isolation. For this situation it is expected to show sidebands of approximately -30dB in the forward direction.

References

[1] C. R. Doerr, N. Dupuis, and L. Zhang, “Optical isolator using two tandem phase modulators,” *Opt. Lett., OL*, vol. 36, no. 21, pp. 4293–4295, Nov. 2011.

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