Modeling and characterization of unidirectional device for feedback insensitive laser

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External optical feedback (EOF) is difficult to avoid in integrated lasers since conventional isolators are incompatible with integration technology. The tandem phase modulators proposed by Doerr et al. are a promising alternative isolator and can be combined with integration. A theoretical analysis for the operation of this component, together with experimental results from a tandem phase modulator operating at 600MHz will be presented and discussed.

Introduction

External optical feedback (EOF), even down to $-50\,\mathrm{dB}$, can have large effects on laser performance as has been recognized long ago [1]. Traditionally these effects have been mitigated by the use of Faraday isolators placed in series with these lasers, allowing light from the laser to pass unperturbed, while heavily attenuating light propagating in the opposite direction. It has however proven to be very difficult to implement such optical isolators with sufficient performance onto photonic integrated circuits (PICs) [2].
An alternative method for a continuous wave laser that is insensitive to EOF was proposed in [3]. It relaxes the requirements on the isolator such that it can be implemented using the method described in [4]. This isolator consists of a spectral filter and two electro refractive modulators (ERMs) that are driven with time-varying electrical signals. The combined ERMs shall be named unidirectional phase modulator (UPM) in this paper and a schematic representation can be found in figure 1. Ideally the device does not affect light propagating in the forward direction, while imposing a phase modulation on light propagating in the backward direction. The influence of imperfections on the performance of the UPM in the forward direction is the focus of this work. This performance will play an important role in the spectral purity of the laser presented in [3]. First a theoretical model is presented, which is subsequently verified by experiments.

Theory

The effect that an ERM has on the light that is passing it is modeled by multiplying the optical field by $\exp(if_n(t))$, where $n = 0$ for the first ERM and $n = 1$ for the second ERM and

$$f_n(t) \equiv A_n \sin(\omega_n t + \phi_n + n\pi/2) + B_n \sin^2(\omega_n t + \phi_n + n\pi/2). \tag{1}$$

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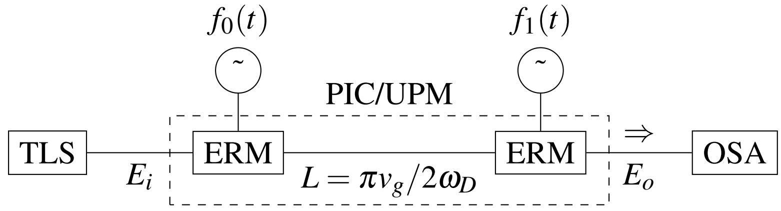

Figure 1: Schematic representation of UPM in measurement setup containing two ERMs driven by electrical signals and spaced by a very specific distance $\pi v_g/2\omega_D$, where v_g is the group velocity, ω_D is the angular frequency of the electrical signals for which the UPM is designed and f_n is the phase modulation imposed on the light by each ERM. A tunable laser system provides the input light, while an optical spectrum analyzer measures the output spectrum.

Non-linearities are modeled using a Taylor-expansion up to second order. The optical field amplitude at the output of the UPM can then be modeled as

$$E_o = \exp\left[i\left(A_0 \sin(\omega_0 t + \phi_0 - \pi/2) + B_0 \sin^2(\omega_0 t + \phi_0 - \pi/2) + \right.\right.$$
$$\left.\left. A_1 \sin(\omega_1 t + \phi_1 + \pi/2) + B_1 \sin^2(\omega_1 t + \phi_1 + \pi/2)\right)\right] E_i \tag{2}$$

In the ideal case we have $A_0 = A_1 \equiv A$, $\omega_0 = \omega_1 \equiv \omega$, $\phi_0 = \phi_1 \equiv \phi$, $B_0 = B_1 = 0$, which results in an output signal in the forward direction without any phase modulation as presented in [4], independent of the values of A, ω and ϕ. In the reverse direction the light is phase modulated and A, ω and ϕ influence the amplitude, frequency and phase of the phase modulation, respectively.

We will now briefly study the effects of imperfections in the driving signals of the modulators. In all cases presented here we will assume only one of the parameters to be imperfect and study the effects of that on the quality of the forward propagating signal. Assuming an otherwise perfect signal the unbalance in amplitude ($A_0 \neq A_1$) can be shown to result in an output electric field of $E_o = \exp(i(A_0 \sin(\omega t - \pi/2) + A_1 \sin(\omega t + \pi/2)))E_i$ by using equation 2. This output electric field is equivalent to one obtained from a single ERM with modulation amplitude $\varepsilon = |A_1 - A_0|$.

An incorrect phase difference between the two ERMs also results in a modulated output signal. The output electric field can then be described by $E_o = \exp(iA(\sin(\omega t - \pi/2) + \sin(\omega t + \pi/2 + \Delta\phi(t))))E_i$, which can also be modeled as a single ERM with modulation amplitude $\varepsilon = 2A\sin(\Delta\phi(t)/2)$ where $\Delta\phi(t)$ is the phase error.

Non-linear effects are modeled using a Taylor expansion. One can show that only even higher-order terms are relevant. If one assumes all even, higher-order terms are negligible except for the second order, only the B parameter from equation 2 needs to be studied and $E_o = \exp(iB(1 - \cos(2\omega t)))E_i$ is obtained. The first term in the exponent will result in a phase offset and is of no consequence to the quality of the output light. The second term will however result in a modulation with amplitude B at twice the frequency of the electrical signal and will therefore deteriorate the forward propagating signal.

Another possible imperfection is related to the spectral content of the electrical signal. The UPM is designed for a very specific frequency ω_D as determined by the spacing of the ERMs (L). When other frequencies are present in the electrical signal, imperfections in the output spectrum occur. As can be seen from equation 2 the effective phase difference

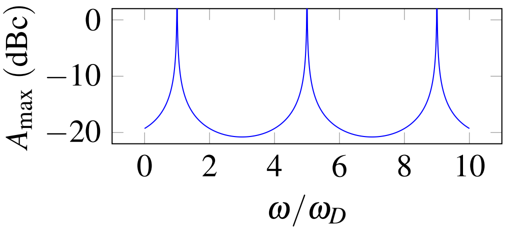

Figure 2: Maximum amplitude of spurious signals at frequency ω, relative to the design frequency ω_D.

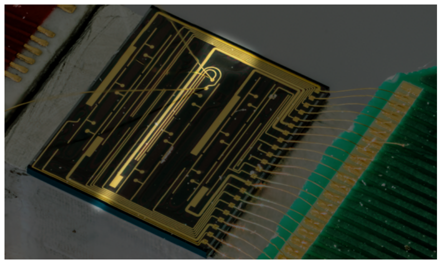

Figure 3: Photograph of the die connected to two PCBs (UPM highlighted).

at which the two modulating signals cancel each other is π rad. If we take a design frequency ω_D, the undesired phase difference can be obtained from the propagation delay between the two ERMs and will be equal to $\Delta\phi = (\omega/\omega_D - 1)\pi/2$. According to the equation for an imperfect phase difference, this leads to a residual modulation of $\varepsilon = 2A\sin((\omega/\omega_D - 1)\pi/4))$ which is smaller than or equal to $2A$ for all frequencies.
Thus, all of the imperfections mentioned result in a residual phase modulation of the light. We model this by replacing the UPM with an ERM with modulation amplitude ε and we assume that the imperfections are relatively small. We then find that the power in the sidebands introduced by the UPM in the forward direction is equal to $(1 - |J_0(\varepsilon)|^2)|E_i|^2$, where J_0 is the zeroth order Bessel function of the first kind. If we require sidebands to be lower than -40 dB relative to the central peak for instance, we find a maximum residual phase modulation of $\varepsilon \leq 0.02$ rad. Using the equations above this translates to a maximum amplitude unbalance of 0.02 rad, a maximum imperfection in the phase of 0.02 rad, $B \leq 0.02$ rad and maximum allowed spurious signals as indicated by the line shown in figure 2, which can all be achieved with current electronics.

Experiments

In order to verify the theoretical predictions made in the previous section, a PIC was manufactured in the SMART platform [5]. A schematic representation of the PIC and the optics and electronics connected to it can be seen in figure 1 and a photograph of the die is shown in figure 3. The device is designed for 600 MHz modulation and therefore has a delay line of 34.7 mm. Both ERMs are 2.5 mm long and are set at -4 V bias.
During the first experiment a sinusoidal signal is applied to the first ERM with amplitude 1.4 V, while the amplitude applied to the second ERM is swept from 0 V to 2.1 V in steps of 0.14 V. During the sweep the output spectrum was measured using a optical spectrometer with a resolution of 5 MHz (APEX 2641B) and from this spectrum the amplitude of a single equivalent phase modulation was determined. The results were fitted to the linear function obtained from the theoretical analysis as $\varepsilon = p_1 + |p_2 A_1 + p_3|$, from which we obtained $\mathbf{p} = [1.3 \times 10^{-2}, -1.5, 1.6]$. The resulting graph is shown in figure 4.
It is clear from this figure that the residual phase modulation is minimal when both electrical signals have approximately the same amplitude, as we would expect. Also it can be seen that there is a linear trend, corresponding to the theoretical predictions. Finally, unexplained imperfections can be seen as the curves do not go toward zero. More research is required to find the cause of this, but one probable cause is polarization conversion in

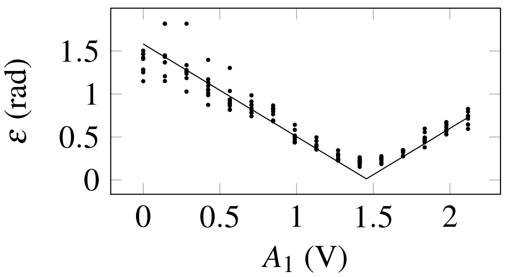

Figure 4: Measurements of the residual phase modulation depth in the forward direction of the UPM as a function of the amplitude of one applied electrical signal together with a fitted line.

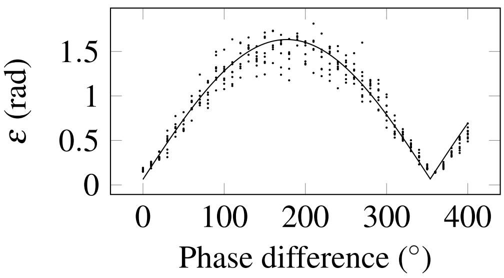

Figure 5: Measurements of the residual phase modulation depth in the forward direction of the UPM as a function of phase mismatch in the applied electrical signals together with a fitted sine curve.

the delay line together with different modulator efficiencies for the TE and TM modes. For the second measurement, both signal generators amplitudes are set to 0.7 V. The phases are varied and the spectrum is again taken to find the residual modulation. The resulting graph is fitted against the expected sinusoidal function from the theoretical analysis as $\varepsilon = p_1 + |p_2 \sin(p_3 x + p_4)|$, from which we obtained $\mathbf{p} = [9.2 \times 10^{-2}, 1.5, 0.50, -0.14]$. The resulting plots are shown in figure 5. Note that the phase offset has not been calibrated and p_4 is therefore not informative on the UPM. In this figure the fitted sine curve is also draw and shows good agreement with our theoretical predictions. Also here, we see the residual modulation being present.

Conclusions

We have modeled the effect of imperfections on light propagating in the forward direction through the UPM presented in [4]. The model provides us with requirements on the amplitude balance, phase matching, non-linearities and spurious signals and harmonics. The correctness of the model has been verified by experiments for amplitude mismatch and phase mismatch and has been found to agree. The model shows that the UPM has negligible impact on the light propagating through the UPM in the forward direction when it is operated using suitable electrical signals. It therefore is a viable candidate for the laser presented in [3].

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