Full Calibration of an InP based Monolithically Integrated Optical Pulse Shaper

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We describe the calibration method and present a full calibration of an InP-based monolithically integrated optical pulse shaper. The 6×6mm^2 chip includes an arrayed waveguide grating separating the spectrum into 20 channels where each channel has an electro-optic phase modulator and an optical amplifier. The calibration method is based on interferometric analysis and is applied to characterize the amplitude and phase of individual device channels as well as the total system response. The calibration information is required for producing predictable pulse shapes.

Introduction

The concept of optical pulse shaping is an active subject of research which has significant applications in ultrafast optics [1], high speed optical communications [2] and coherent anti-stokes Raman scattering (CARS) microscopy [3]. A commonly used method is the so-called Fourier transform optical pulse shaping technique. In this approach, a spectrally dispersive element is used to decompose the incident optical pulse into its constituent spectral components. The phase and amplitude of the spectral components are then modulated by a spatial mask and an optical grating is then used to combine the spectral components to form the shaped pulse.

Photonic integration technology is capable of providing the required functionalities for building such complex systems on an optical chip. In [4] we have reported on design and realization of a monolithically integrated optical pulse shaper. Fabrication has been carried out in a standardized generic photonic integration platform.

Fig. 1 shows a microscope image of the realized chip which is designed with a reflective geometry. The light from the optical pulse source is injected into the pulse shaper chip via an anti-reflection coated facet. The pulsed signal passes through an AWG which decomposes it into spectral components. Each component passes through a PM and an SOA and is then reflected back from a facet with a high-reflection coating. The PMs and SOAs are used to manipulate the spectral phase and amplitude of the components in order to achieve the desired pulse shape. The spectral components are then recombined in the AWG and return through the input/output waveguide. The two directions are separated by a circulator outside the chip. In the reflective geometry, spectral components pass through optical elements twice; therefore the device is more compact, the PM's and SOA operate more efficiently and there is no need for matching the transmission properties of two AWGs.

Fourier Transform Pulse Shaping

A pulse shaper device is commonly combined with a mode-locked laser source which generates the input pulses. The input optical pulses pass through the pulse shaper which is used to manipulate the amplitude and phase of spectral components in order to synthesize a desired output pulse shape. In this scenario, the input pulse shape (spectral

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This work is supported by the Dutch IOP Photonic Devices managed by the Technology Foundation STW and Agentschap NL and in part by the European FP7 EuroPIC project.

amplitude and phase) is known and the required control settings on the pulse shaper need to be calculated to achieve the required optical output. The frequency-domain response of the pulse shaper, $H(\omega)$, is the key to understanding the principle of the Fourier transform pulse shaping technique which is shown schematically in Fig.2. $H(\omega)$ is the Fourier transform of the system impulse response, $h(t)$, and relates the input/output pulse shapes as $E_{\text{out}}(\omega) = H(\omega) \times E_{\text{in}}(\omega)$.
Therefore, calibration of the pulse shaper is equivalent to finding the frequency response of the system and the effect of control signals on the response.

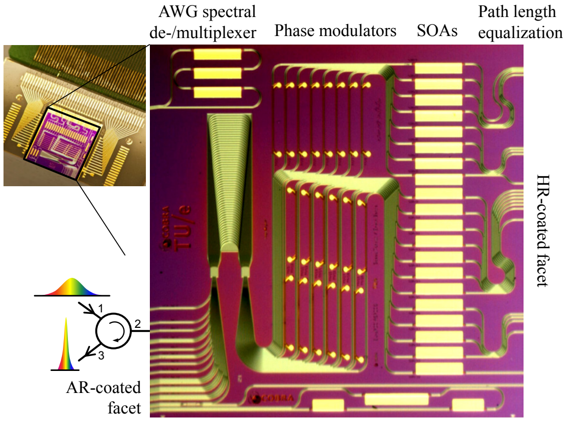

Fig.1. Microscope image of the realized pulse shaper. The chip is mounted on a subcarrier which is connected to a printed circuit board and provides the control signals.

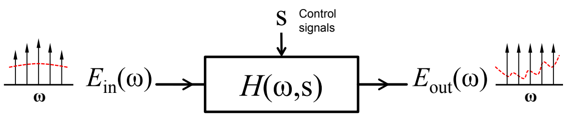

Fig.2. Schematic representation of the Fourier transform pulse shaping approach. E is the electric field; $H(\omega)$ is the frequency-domain response of the pulse shaper; the term s stands for the control signals.

Calibration Method

The total response of the pulse shaper chip is a linear summation of the frequency responses of the operating channels. If the total response of the system is H_{tot}, we assume $H_{tot}(\omega,s) = \sum_{k=1}^{N} H_k(\omega,s_k)$ in which N is number of channels, s_k stands for the control signal in the channel and H_k is the individual channel response. It is convenient to define $H_k(\omega,s_k) = H_{Rk}(\omega) \times M_k(s_k)$ in which $H_{Rk}(\omega)$ is the channel response at a reference state of control signals and let the function $M_k(s_k)$ account for the effect of applied control signals on the phase and amplitude of the light signal in each channel. For instance, in an ideal case where the gain section only affects the spectral amplitude and the phase modulator only affects the phase, the complex function M can be written as $M(\alpha,\beta) = \mathrm{A}(\alpha)e^{j\Phi(\beta)}$, in which A and Φ are real functions of the amplifier and phase modulator bias settings, α and β.
Therefore, once the channels are individually characterized in the reference state (H_{Rk}), and the effect of applied control signals on the phase and amplitude of the light signal (M_k) in each channel is determined, the total response of the pulse shaper (H_{tot}) can be calculated by simply adding the frequency responses of the channels (H_k). The advantage of this method is that the functions H_{Rk} and M can be measured separately.
In order to find the channel response, we use an interferometric measurement method. Fig.3 shows the schematic drawing of the setup which is configured in the form of a Mach-Zehnder interferometer. In this setup, the light from an optical source is divided between the reference and the device arms. The device arm includes the device under test (DUT) and a time-delay element, which is a path length difference between the reference and the device arms. The signals of the two arms are then combined and the optical power is recorded. In this method, the frequency of the optical source is tuned and the optical power is measured at each frequency.
We define the electric field of the signal generated by the optical source to be $\mathscr{E}(t) = E_0 e^{j\omega t}$. Therefore, the signal in the reference arm is represented as $\mathscr{E}_1 = E_0$ in frequency domain. For convenience and without loss of generality, we have assumed a

splitting ratio of unity and a zero delay in the reference arm. The electric field which has passed through the device arm is then $\mathscr{E}_2 = E_0 \times e^{-j\omega\tau} \times H(\omega)$ where τ is the time delay in the device arm and $H(\omega)$ is frequency response of the DUT.

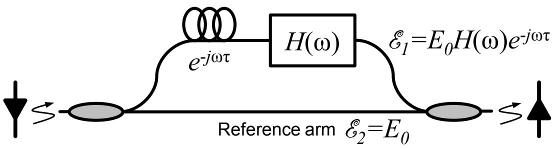

Fig.3. Schematic drawing of the interferometric setup in the Mach-Zehnder configuration.

If we define $H(\omega)$ in terms of the real and imaginary parts as $H(\omega) = \alpha(\omega)e^{j\varphi(\omega)}$, the measured optical power, $P_{\det}$, can be stated as

$$P_{\det}(\omega) \sim \left|\mathscr{E}_1 + \mathscr{E}_2\right|^2 = E_0^{\,2}\left|1 + \alpha(\omega)e^{j\varphi(\omega) - j\omega\tau}\right|^2 = 1 + \alpha^2(\omega) + \alpha(\omega)\cos\left(\varphi(\omega) - \omega\tau\right)$$

Now we examine the measured signal in time domain.

$$p_{\det}(t) = \mathscr{F}^{-1}\left\{P_{\det}(\omega)\right\} \sim \int_{-\infty}^{\infty}\left[1 + \alpha^2(\omega) + \alpha(\omega)\cos\left(\varphi(\omega) - \omega\tau\right)\right]e^{j\omega t}d\omega .$$ Hence

$$p_{\det}(t) \sim \delta(t) + \underbrace{\int_{-\infty}^{\infty}\alpha^2(\omega)e^{j\omega t}d\omega}_{\text{A}} + \underbrace{\int_{-\infty}^{\infty}\alpha(\omega)\frac{e^{j(\varphi(\omega)-\omega\tau)} + e^{-j(\varphi(\omega)-\omega\tau)}}{2}e^{j\omega t}d\omega}_{\text{B}}$$ where $\delta(t)$ is the Dirac delta and

$$\text{A} = \int_{-\infty}^{\infty}\alpha^2(\omega)e^{j\omega t}d\omega = \int_{-\infty}^{\infty}\left|H(\omega)\right|^2 e^{j\omega t}d\omega = \mathscr{F}^{-1}\left\{H(\omega)\times H^*(\omega)\right\} = h(t)\otimes h^*(-t)$$

$$\text{B} = \int_{-\infty}^{\infty}\alpha(\omega)\frac{e^{j(\varphi(\omega)-\omega\tau)} + e^{-j(\varphi(\omega)-\omega\tau)}}{2}e^{j\omega t}d\omega$$

$$\sim \int_{-\infty}^{\infty}\alpha(\omega)e^{j\varphi(\omega)}e^{j\omega(t-\tau)}d\omega + \int_{-\infty}^{\infty}\alpha(\omega)e^{-j\varphi(\omega)}e^{j\omega(t+\tau)}d\omega = h(t-\tau) + h^*(-(t+\tau))$$

Therefore, $p_{\det}(t) \sim \delta(t) + h(t)\otimes h^*(-t) + h(t-\tau) + h^*(-(t+\tau))$ in which, * is the complex conjugate and ⊗ represents the convolution operation.

In case of the integrated pulse shaper, $h(t)$ corresponds to a physical (causal) system and has a finite duration in time. Therefore, the term A is limited in time and goes to zero for values of t larger than the duration of $h(t)$. This means that if a proper value of τ (larger than the duration of the impulse response) is chosen, the effect of the system impulse response, i.e. $h(t-\tau)$, does not temporally overlap with other terms, and therefore it is possible to filter out the part of the signal which corresponds to $h(t)$ and equivalently achieve $H(\omega)=\mathscr{F}\{h(t)\}$. The method could be applied to measure the individual channel response in the reference state as well as the total system response.

Experimental Results

The integrated pulse shaper has a reflective geometry. If a cleaved fiber tip is used to inject the optical signal to the chip, a Michelson interferometer is formed. In this case, the reflection from the tip of the fiber is considered as the reference signal and the time delay of the device arm corresponds to the total length of the chip. It is possible to characterize device channels individually. If an SOA is not biased, it effectively absorbs the light in the corresponding channel. On the other hand, if the SOA is biased to provide enough gain, the signal which goes through the channel and return to the input interferes with the reflected signal from the tip of the cleaved fiber.

We have used a continuously tunable laser source to sweep the input signal wavelength and recorded the optical power in steps of 1pm. The optical power of the source is kept below 3dBm to make sure nonlinear effects in SOAs, such as saturation and self-phase

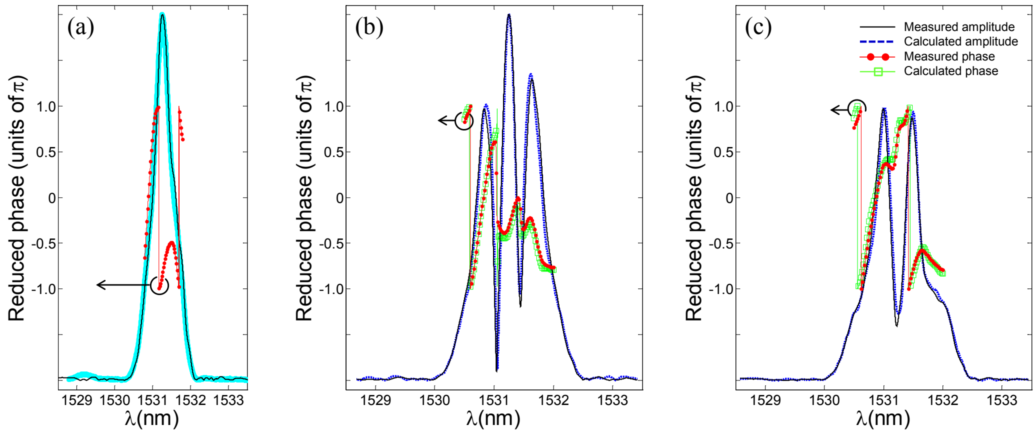

Fig.4. Normalized amplitude and phase of the channel/system response. (a) Reference state (V_{PM}=0V, I_{SOA}=40mA) response of channel 10 (thin line) and the shape of the AWG channel (thick line). (b) Measured and calculated reference state total response of channels 9, 10 and 11. (c) Measured and calculated total response with V_{PM10}=2V.

modulation, does not disturb the operation. We measure the interference signal in order to determine the frequency response of each channel, as described in the previous section. The measurement is repeated for all the channels. Fig.4(a) shows the measured response (normalized amplitude and phase) of channel 10 at V_{PM}=0V and I_{SOA}=40mA. The measured shape of the AWG channel 10 is given for comparison as well.

In order to confirm the proposed calibration method, we follow the steps below. For convenience, we have considered only channels 9, 10 and 11.

1- First we bias the SOA in the channels, one at a time, and measure the individual channel response at I_{SOA}=40mA and V_{PM}=0V. This is defined as the channel response at the reference state.
2- Next, we bias the three channels together and measure the total response. We observe that the measured total response matches with the summation of individual channel responses. The results is shown in Fig.4(b).
3- Then we consider the effect of a control signal. For instance, we apply a reverse bias on the PM in channel 10 (V_{PM}=2V). Phase tuning curves of PMs [4], show that the applied voltage corresponds to a ~π phase change in channel 10. We include the effect of this phase change in addition to the reference state channel response and then calculate the system response by simply adding the response of the three channels. The result is shown in Fig.4(c). The measured total system response at V_{PM10}=2V is given for comparison.

Conclusion

We have described and applied an interferometric analysis method to characterize the amplitude and phase response of an integrated pulse shaper. The calibration procedure involves characterization of individual channels at a reference state of control signals and separate evaluation of the effect of control signals on optical elements, i.e. phase modulators and SOAs. The total system response is verified to be a linear summation of individual channel responses.

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