

An InP-Based Optical Equalizer Monolithically Integrated With a Semiconductor Optical Amplifier

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Abstract—We present the first optical equalizer realized on Indium Phosphide material that is also monolithically integrated with a semiconductor optical amplifier. We show that the device can mitigate inter-symbol interference arising from narrowband optical filtering of 40-Gb/s non-return-to-zero data. Significant improvement in the measured bit-error rates after optical equalization of the filtered signal is reported. It is shown that the device can also mitigate the impairments arising from residual chirp and electrical filtering in the transmitter and receiver.

Index Terms—Integrated optical devices, monolithic integration, optical equalizer, semiconductor optical amplifier (SOA).

I. INTRODUCTION

WITH data rates increasing beyond 40 Gb/s, it is becoming more challenging to achieve the required bandwidths in optical communication systems. Optical equalizers [1] have been shown to compensate the inter-symbol interference (ISI) resulting from fiber dispersion, insufficient bandwidth in a system [2], [3], or nonlinear impairments from a semiconductor optical amplifier (SOA) [4]. The transmitter may be limited by both the electrical bandwidth of its modulator and driver, and by the bandwidth of the optical multiplexing system. An optical equalizer can play a critical role in achieving higher data rates and it would be advantageous to have a device that is sufficiently compact to allow packaging in the transmitter module or ultimately to be monolithically integrated with the laser and modulator. Since optical equalizers introduce loss as part of the equalization process, the capability to integrate a gain element would allow the transmitter power to be maintained. This makes the integration of an equalizer on an Indium Phosphide (InP)-based platform, which has a smaller bend radius and can provide optical amplification and ultimately integration with the rest of the transmitter, an attractive option.

Here, we present the first optical equalizer on an InP platform that is also monolithically integrated with an SOA. We show that this device can be used to mitigate the impairments arising from narrowband optical filtering. We specifically characterize the degradation of the bit-error rates (BERs) arising

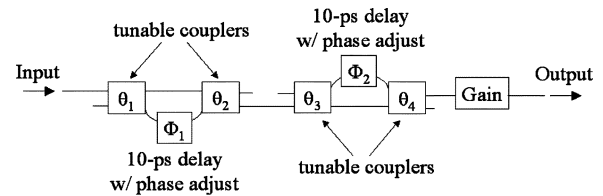


Fig. 1. Filter function of two-stage optical equalizer with gain element. The relative path delay T between two taps in each stage is set to 10 ps.

from ISI due to narrowband filtering on an optical channel carrying nonreturn-to-zero (NRZ) data at 40 Gb/s. We show that this device can improve the measured BER by mitigating ISI arising from residual chirp and electrical filtering in the transmitter and receiver. While preliminary results from the device were recently reported [5], we present improved results along with more detailed characterization of the device in this letter.

II. DEVICE DESIGN AND FABRICATION

A two-stage optical equalizing filter, with two taps in each stage, is implemented with a gain element as shown in Fig. 1. The filter is realized using two cascaded Mach-Zehnder interferometers (MZIs). Each MZI has a relative path delay T of 10 ps between its two arms, giving a free spectral range of 100 GHz. Each MZI has two tunable couplers and phase shifters that are used to control the phase and amplitude response of the equalizer. Each tunable coupler [6] is designed using two coupled MZI, one with a fixed relative phase delay, δ ($= 120^\circ$), between its two arms and the other with thermo-optic phase shifters that tune the phase θ_k to control the coupling ratio. The coupling ratio of this tunable coupler is less sensitive to variations in wavelength and fabrication and is defined by the functions $|f(\theta_k)|^2$ and $|g(\theta_k)|^2$ in (1). Thermo-optic phase shifters are also used to tune the phases Φ_j of each stage of the filter.

The function representing the filter's frequency response $H(\omega)$ is given by

$$\begin{aligned}
 H(\omega) &= [f(\theta_1)g(\theta_2) + f(\theta_2)g(\theta_1)e^{j\omega T} e^{j\phi_1}] \\
 &\quad \times [f(\theta_3)g(\theta_4) + f(\theta_4)g(\theta_3)e^{j\omega T} e^{j\phi_2}] \\
 f(\theta_k) &= \frac{1}{\sqrt{2}} \left[-\cos\left(\frac{\theta_k - \delta}{2}\right) + j \sin\left(\frac{\theta_k + \delta}{2}\right) \right] \\
 |f(\theta_k)|^2 &= \frac{1}{2} [1 + \sin \delta \sin \theta_k] \\
 g(\theta_k) &= \frac{1}{\sqrt{2}} \left[-\sin\left(\frac{\theta_k - \delta}{2}\right) + j \cos\left(\frac{\theta_k + \delta}{2}\right) \right] \\
 |g(\theta_k)|^2 &= \frac{1}{2} [1 - \sin \delta \sin \theta_k]. \tag{1}
 \end{aligned}$$

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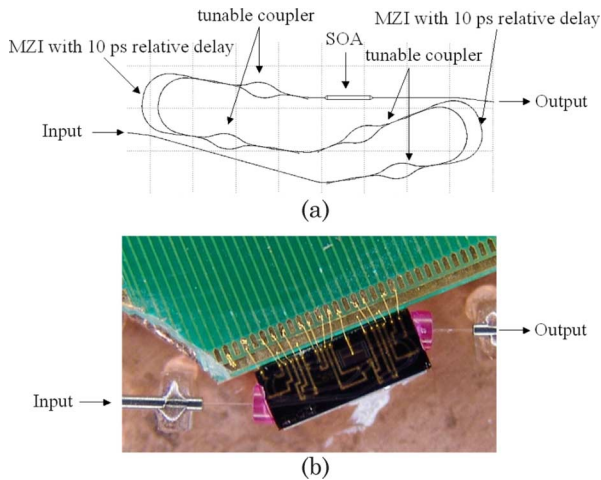


Fig. 2. (a) Layout of optical equalizer monolithically integrated with an SOA. (b) Packaged device.

The fabrication of the optical equalizer monolithically integrated with an SOA is made possible using a passive–active integration scheme [7], which allows monolithic integration of low-loss passive optical waveguides (typically ~ 1 dB/cm) and an SOA. The wafer is grown by low-pressure metal–organic chemical vapor deposition (MOCVD) and consists of step-graded InGaAsP slab layers ($\lambda_g = 1.1, 1.2,$ and $1.3 \mu\text{m}$), a 105-nm-thick rib layer ($1.3 \mu\text{m}$), and an active layer with four compressively strained InGaAsP quantum-well layers separated by compensating tensile strained barrier layers. The SOAs fabricated from this material platform exhibit gain for TE-polarized light only. The gain peak of the SOA is around $1.55 \mu\text{m}$. In a first step, the active layer is removed everywhere except for the area that will be occupied by the SOA. Subsequently, the passive waveguides (coupler and access waveguides) and the SOA mesa are etched. This is followed by the overgrowth of a current blocking layer, an isolation step, a second overgrowth, and two metallization steps, which form contacts to the SOA and heaters for tuning the filters and couplers. The active waveguide of the SOA is 1 mm long and $\sim 1.2 \mu\text{m}$ wide. The minimum bend radius of the passive waveguide is $620 \mu\text{m}$. The total propagation length in the passive waveguides of this device is ~ 25 mm. A schematic layout of the device is shown in Fig. 2(a). The access waveguide at the facet is angled by 7° to suppress reflections but no AR-coating was applied at the time of characterization. In order to pass individual currents through the phase shifters and the SOA, and to attach fibers, the device is indium soldered to a copper stud. Electrical current is supplied through connection to a fan-out board. Lensed fibers are then attached to the device whose dimensions are 8.5×3.5 mm. The packaged device is shown in Fig. 2(b).

III. EXPERIMENT AND RESULTS

NRZ data with a pseudorandom bit stream (PRBS) of length $2^{31}-1$ was modulated at 40 Gb/s on the light from an external cavity laser at 1545.31 nm using a dual-drive LiNbO₃ Mach–Zehnder modulator. The transmitter was characterized by measuring the back-to-back BER versus received optical

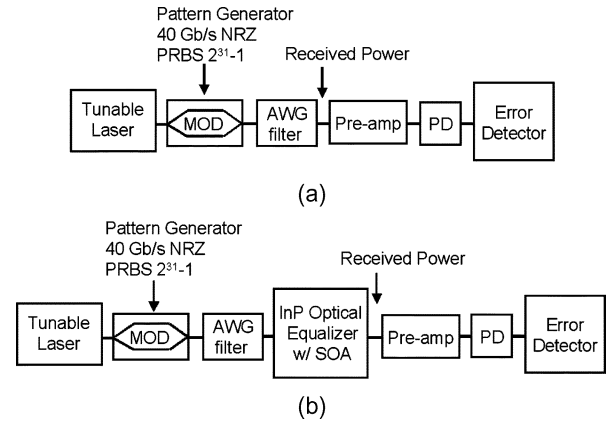


Fig. 3. Measurement setup: (a) BER measured after narrowband optical filtering through an AWG and (b) BER measured after passing optically filtered signal through InP monolithically integrated optical equalizer and SOA. PD is a high-speed photodetector.

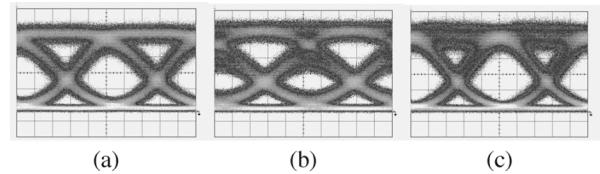


Fig. 4. Eye diagrams at 40 Gb/s: (a) for back-to-back transmission, (b) after narrowband optical filtering through AWG, and (c) after passing optically filtered signal through optical equalizer monolithically integrated with an SOA. Horizontal scale: 5 ps/div. Vertical scale: arbitrary units.

power using an optically preamplified receiver. A 1-nm-wide optical filter was placed between the optical preamplifier and the high-speed photodetector. A BER of 10^{-9} was measured for a received optical power of -28.0 dBm. The modulated light was then passed through an optical filter, which was an arrayed waveguide grating (AWG), whose transmission maximum was centered at the wavelength of the laser. The experimental setup is shown in Fig. 3(a). The amplitude response of the optical filter was approximately Gaussian with a 3-dB full-width of 36 GHz with almost negligible dispersion. The filter imposes strong ISI leading to deterioration in the measured BER as seen in Fig. 5, with an error floor at $\sim 10^{-7}$. The effect of narrowband optical filtering and the presence of ISI can be seen in the eye diagram in Fig. 4(b).

The distorted optical signal was passed through the optical equalizer monolithically integrated with an SOA described in the previous section, as shown in Fig. 3(b). The SOA biased at 150 mA was at the output side of the device, as shown in Fig. 2. By appropriately choosing the equalizer response using the tunable couplers and phase shifters, the floor on the BER curve was removed and a BER of 10^{-9} was measured for a received optical power of -29.9 dBm, as shown in Fig. 5. The eye diagram of the optical signal after equalization is shown in Fig. 4(c), which shows a mitigation of ISI arising from the narrowband optical filtering along with an improvement in the eye opening and extinction ratio. The BER curve shows ~ 2 dB improvement in the receiver sensitivity compared to that measured for back-to-back transmission, with no indication of an error floor at BER as low as 10^{-10} .

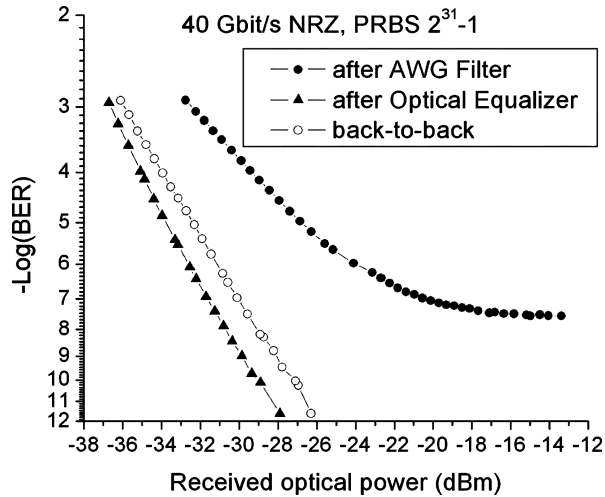


Fig. 5. Measured BER versus received power at 40 Gb/s for back-to-back transmission, after optical filtering induced ISI, and after mitigating ISI impairments using monolithically integrated optical equalizer and SOA.

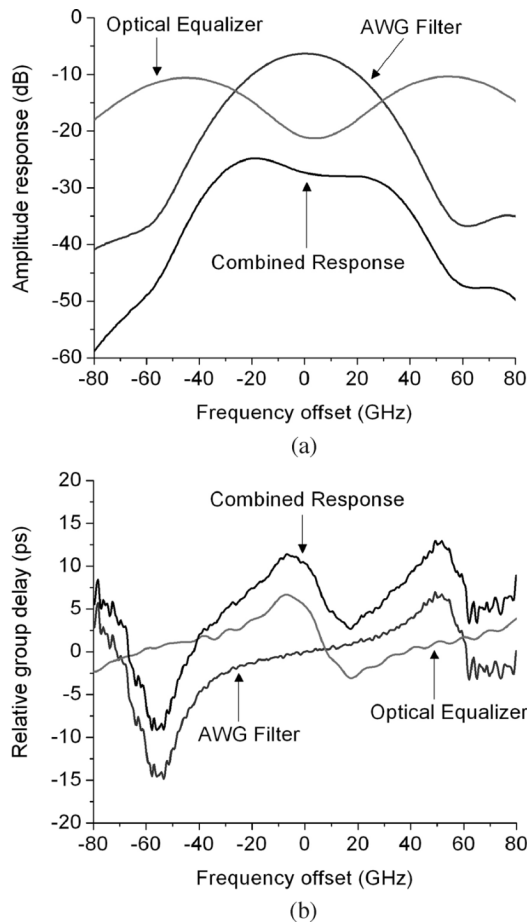


Fig. 6. (a) Amplitude response and (b) relative group delay versus frequency offset for AWG, optical equalizer, and their combination.

The frequency response of the amplitude and relative group delay of the AWG filter and the optical equalizer optimally set to mitigate the ISI from the narrowband filtering were measured using an optical vector analyzer and are shown in Fig. 6.

As expected, the optical equalizer creates a near complementary filter amplitude response to that of the narrowband AWG filter, resulting in a combined amplitude response that exhibits a wider bandwidth than the AWG filter. However, the combined amplitude response and relative group delay are not entirely flat versus frequency, indicating that the equalizer is doing more than simply compensating the narrowband AWG filter by also compensating for other impairments present in the system. This is confirmed by the measured BER versus received power after equalization being better than that measured for back-to-back transmission. By appropriate choice of the amplitude and phase response of the equalizer, the combined response with the narrowband AWG filter improves the receiver sensitivity by mitigating the ISI arising from any residual chirp and electrical filtering in the transmitter and receiver.

IV. CONCLUSION

We have demonstrated the first optical equalizer on an InP-platform and it is also monolithically integrated with an SOA. We have shown that this equalizer can mitigate the ISI imposed by narrowband optical filtering and can significantly improve the measured BER on NRZ data at 40 Gb/s. Furthermore, we have shown that the equalizer can also mitigate impairments in the transmitter and receiver and improve receiver sensitivity. The SOA provides optical amplification that compensates for the loss of the equalizing filter and the coupling losses between the optical fiber and the waveguide on the InP chip. The InP platform opens up the opportunity for integration of such devices with lasers and modulators.

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