Operating Speed Extension of SOA External Modulator Using Microring Resonator

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Abstract— We propose to employ a passive single microring resonator (MRR) for extending the modulation speed of semiconductor optical amplifiers (SOAs), which are configured as external modulators. The MRR efficiently acts as notch filter and compensates for the pattern-dependent distortion at the output of the electrically modulated SOA. By conducting numerical simulation, we specify a combination of feasible MRR radius and detuning which allows to achieve significant improvements on the performance of the SOA, at a data rate well beyond its limited modulation bandwidth.

1. INTRODUCTION

Semiconductor optical amplifiers (SOAs) have recently been receiving intense research interest for use as external modulators. This possibility, which is being explored in various applications [1], is spurred by SOAs attractive properties of low power consumption, broad gain bandwidth and compactness. The ultimate goal is to have SOAs provide both data amplification and modulation, thus overcoming the limitations encountered by other optical modulators [2].

Despite theoretical predictions that SOAs could be employed as fast external modulators [3], yet the practically achievable data speeds are not sufficient for supporting the diverse application needs. In fact a serious constrain is imposed by the SOA modulation bandwidth, which is below 1 GHz due to the SOA finite differential carrier lifetime [4]. This limitation impairs the quality of the modulated optical signal at the SOA output, thus obstructing the use of this active element beyond pure amplification. In order to overcome this difficulty, a widely adopted option exploits optical filtering to manipulate the instantaneous frequency deviation components that are incurred together with the waveform distortion [5]. These components are induced by changes of the refractive index of the active medium, which accompany those of the carrier density by the direct modulating current [2]. For this purpose various filter technologies have been employed [1], and references 11–14 therein]. In this paper we propose to apply a passive single microring resonator (MRR) as notch filter [6] for extending the modulation speed of directly modulated SOAs. This scheme features structural simplicity, ultra compact and small size, compatibility with microelectronic fabrication processes, periodic comb-like transmission profile, better wavelength selectivity, enhanced fine tuning capability, high contrast ratio, improved operational stability and availability of different material systems. These attractive operating and practical characteristics render it an appealing solution for allowing conventional SOAs to be used as external modulators at enhanced data rates.

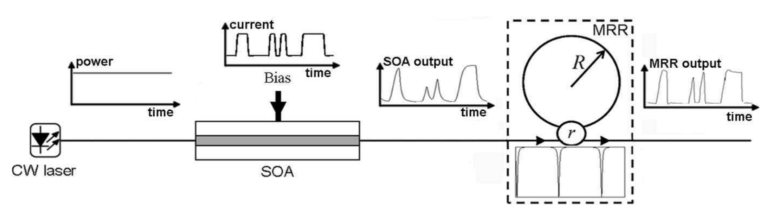

Figure 1: Configuration of directly modulated SOA and MRR-based notch filter.

2. CONCEPT

Figure 1 depicts the block diagram of the setup under consideration, which comprises of a SOA followed by a MRR of radius R, field transmission coefficient r, round-trip amplitude attenuation factor τ and material effective refractive index n_{eff}. The SOA is biased at a constant current, I_{dc}, which has an offset of $\pm I_o$ induced by an applied RF data signal of repetition rate B_{rep}. This means that the SOA total driving current varies between $I_{dc} - I_o$, which must be over the SOA current at transparency, I_{tr}, and $I_{dc}+I_o$, which must not exceed the maximum current allowed to drive the SOA without damaging it. Then the SOA current modulation is imprinted on an optical signal of constant power over time, which is launched from a continuous wave (CW) laser source. This process would normally produce a replica of the applied electrical signal at the SOA output. However this is not achieved when the SOA modulation bandwidth, B_{mod}, is smaller than the bandwidth that corresponds to the rate of the applied excitation, which in case of NRZ data format is $B_{exc}=B_{rep}/2$ [7]. The negative by-product of this mismatch is the occurrence of pattern effects and subsequently of performance defaults, namely the lack of uniformity between pulses of the same binary content and the poor distinction between pulses of different binary content. Nevertheless, these impairments can be mitigated in the time domain by taking advantage of those that concurrently manifest in the spectral domain. More specifically, the encoded pulses acquire an instantaneous frequency deviation (IFD) across them, which is negative at the leading edge of the marks, positive at the trailing edge of the marks and levels-off across the spaces. Therefore the key for lessening the pattern-dependent consequences associated with the SOA direct modulation is to properly compensate for these components. This can be achieved by exploiting the notch filtering behavior that a single MRR can exhibit under properly defined and applied operating conditions [6]. These conditions involve and link the spectral characteristics of the input and encoded optical signal and the comb-like transfer function (TF) of the MRR, which is shown in Fig. 1 at the bottom of the dashed-dotted box. Now in order to restore the quality of the encoded signal we must make the components with negative IFD to lie in the right-hand falling slope against the peak of the MRR TF. Additionally we must force those being stronger in magnitude to fall closer to the MRR notch, which occurs at resonance, than those being weaker in magnitude. In this manner the former components will be less transmitted than the latter. Moreover, we must confine the components with positive IFD around the flat portion of the MRR TF so that they experience almost the same transmittance. Finally, we must preserve the original carrier which bears the modulated information. Then the notch filtering action transforms these adjustments into opposite amplitude changes that those after the SOA [1], and thus the MRR alleviates the performance degradations due to the SOA direct modulation.

3. SIMULATION

The operation of the setup in Fig. 1 is modeled by taking into account the responses of the SOA and MRR. For the SOA this is done through the following differential Equation [3]

$$\frac{dh(t)}{dt}=\frac{\Gamma\alpha N_{tr}\left[\dfrac{I(t)}{I_{tr}}-1\right]L-h(t)}{T_{car}}-\frac{P_{in,CW}}{P_{sat}T_{car}}\Big\{\exp\big[h(t)\big]-1\Big\} \tag{1}$$

where $h(t)$ is the SOA power gain integrated over its length, $L=2\,\text{mm}$, $\Gamma=0.25$ is the SOA confinement factor, $\alpha=3.3\times10^{-20}\,\text{m}^2$ is the SOA differential gain, $N_{tr}=0.15\times10^{24}\,\text{m}^{-3}$ is the SOA carrier density required for transparency, $I_{tr}=75$ mA is the SOA current required for transparency, $T_{car}=312$ psec is the SOA carrier lifetime, $P_{sat}=10\,\text{dBm}$ is the SOA saturation power and $P_{in,CW}=-5\,\text{dBm}$ is the power of the input CW optical signal. Using these values for the SOA parameters, Equation (1) is numerically solved as in [6] for the time-varying bias current, $I(t)$, which is assumed to be a pseudo-random sequence of NRZ pulses having duration 200 ps and equal rise and fall time of 35 ps. This allows to calculate $h(t)$ and subsequently the electric field at the SOA output

$$E_{SOA}(t)=\sqrt{P_{in,CW}}\exp\Big[\big(1/2(1-j\alpha\big)h(t)\Big] \tag{2}$$

where $\alpha=10$ is the SOA linewidth enhancement factor. Note that (2) is normalized so that its squared modulus represents power, i.e., $P_{SOA}(t)=|E_{SOA}(t)|^2$ [7]. On the other hand the MRR response is conveniently described by the compact mathematical form [6]

$$T_{MRR}(\lambda)=\frac{r-\tau\exp\Big[jn_{eff}4\pi^2R\big((\lambda-\Delta\lambda)/\lambda^2\big)\Big]}{1-r\tau\exp\Big[jn_{eff}4\pi^2R\big((\lambda-\Delta\lambda)/\lambda^2\big)\Big]} \tag{3}$$

where $r=\tau=0.95$, in accordance to the condition of critical coupling, which must be satisfied in order for the MRR to efficiently act as notch filter [6], and $n_{eff}=1.41$. Now since the SOA response is time-dependent whilst the MRR response is wavelength-dependent, finding the electric field at the MRR output requires to apply on (2) the Fast Fourier Transform (FFT), $F\{\cdot\}$, in Matlab software and convolve it with (3). Finally, the convolution product is converted back into the time domain using inverse FFT, $F^{-1}\{\cdot\}$. Hence $E_{MRR}(t) = F^{-1}\{F[E_{SOA}(t)]T_{MRR}(\lambda)\}$ and accordingly $P_{MRR}(t) = |E_{MRR}(t)|^2$.

4. RESULTS

Tailoring the MRR as described in Section 2 critically requires to properly select its radius for the following reasons [6]. First, this parameter determines the wavelength distance, or free spectral range (FSR), between adjacent maxima in the MRR transfer function, as expressed through $FSR = \lambda_{data}^2/(2\pi n_{eff}R)$, where $\lambda_{data} = 1540\,\text{nm}$ is the reference wavelength. Second, it determines the exact notch wavelength position, λ_{notch}, through the condition of resonance, $2\pi R n_{eff} = m\lambda_{res}$, where m is a non-zero integer and $\lambda_{res} \equiv \lambda_{notch}$. At the same time it determines the range, $FSR/2$, within which the MRR is allowed to be detuned. This detuning, $\Delta\lambda$, must be such that the MRR transmission peak is offset at a shorter wavelength than that of the optical carrier, i.e., blue-shifted. Thus in order to find an appropriate combination of R and $\Delta\lambda$ we investigated, based on the model formulated in the previous section, their impact on three important performance metrics. These include the maximum amplitude difference between marks ($AD_{1,\max}$), between spaces ($AD_{0,\max}$) and between marks and spaces ($AD_{1/0,\max}$), which must be as small as possible in the two first cases and as high as possible in the third. The obtained results are shown in Figs. 2 and 3.

More specifically, from Fig. 2(a) we notice that $AD_{1,\max}$ is reduced at the output of the MRR provided that the radius of the latter is an integer multiple of 4 µm, while it is hardly affected by the other scanned values of this parameter. Furthermore, for fixed R values which comply with the aforementioned condition, $AD_{1,\max}$ is reduced with the increase of the detuning and reaches a minimum when $\Delta\lambda$ is confined around 0.55 nm. A similar variation is observed in Fig. 2(b) for $AD_{0,\max}$, while the opposite happens in Fig. 2(c) for $AD_{1/0,\max}$. Then according to this evidence it is possible to properly select R and $\Delta\lambda$ so that their effect is favorable on all considered performance factors simultaneously. In fact the combination $R = 4\,\mu\text{m}$ and $\Delta\lambda = 0.6$ nm drastically reduces $AD_{1,\max}$,

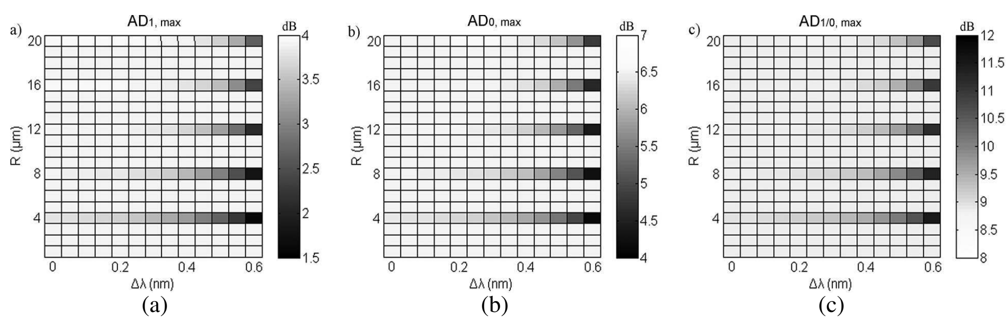

Figure 2: Variation of performance metrics against MRR radius, R, and detuning, $\Delta\lambda$. (a) $AD_{1,\max}$, (b) $AD_{0,\max}$, (c) $AD_{1/0,\max}$.

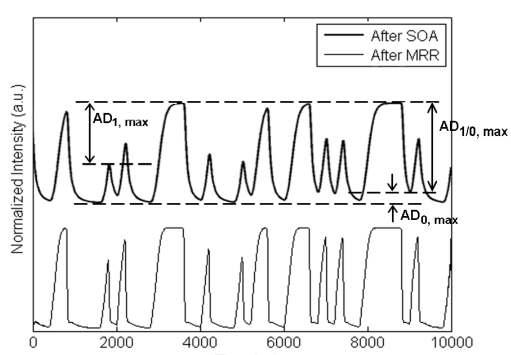

Figure 3: Simulated temporal waveforms of directly modulated optical signal at semiconductor optical amplifier (upper trace) and MRR-based notch filter (lower trace) output.

$AD_{0,\max}$, and increases $AD_{1/0,\max}$, by 2.3 dB, 2.38 dB and 2.65 dB, respectively, compared to the SOA only. Thus the MRR-based notch filter strongly suppresses the peak amplitude fluctuations between marks, between spaces, as well as the level of the spaces. This improvement is monitored in the lower trace of Fig. 3, in contrast to the severely distorted pattern waveform right after the SOA shown in the upper trace of the same figure. From the lower trace it is also apparent that the profile of the encoded data stream is restored and resembles that of the electrically applied signal.

5. CONCLUSION

We have presented preliminary simulation results, which provide a first confirmation that a passive single MRR configured as notch filter can be used to compensate for the pattern-dependent degradation in a SOA of limited modulation bandwidth. Further work is underway in order to fully characterize the capability of the proposed scheme to extend the data rate at which the SOA can operate as external modulator with improved performance.

REFERENCES

1. Zoiros, K. E. and P. Morel, "Enhanced performance of semiconductor optical amplifier at high direct modulation speed with birefringent fiber loop," *AIP Advances*, Vol. 4, No. 7, 077107/1–7, 2014.
2. Udvary, E. and T. Berceli, "Improvements in the linearity of semiconductor optical amplifiers as external modulators," *IEEE Trans. Microw. Theory Techn.*, Vol. 58, No. 11, 3161–3166, 2010.
3. Ali, M. A., A. F. Elrefaie, and S. A. Ahmed, "Simulation of 12.5 Gb/s lightwave optical time-division multiplexer using semiconductor optical amplifiers as external modulators," *IEEE Photon. Technol. Lett.*, Vol. 4, No. 3, 280–283, 1992.
4. Connelly, M. J., *Semiconductor Optical Amplifiers*, Kluwer Academic Publishers, The Netherlands, 2002.
5. Inoue, K., "Optical filtering technique to suppress waveform distortion induced in a gain-saturated semiconductor optical amplifier," *Electron. Lett.*, Vol. 33, No. 10, 885–886, 1997.
6. Rizou, Z. V., K. E. Zoiros, and A. Hatziefremidis, "Semiconductor optical amplifier pattern effect suppression with passive single microring resonator-based notch filter," *Opt. Commun.*, Vol. 329, 206–213, 2014.
7. Agrawal, G. P., *Fiber-Optic Communication Systems*, Wiley, New York, 2002.