Dynamic optical memory based on light trapping in a ring resonator using asymmetric grating assisted codirectional couplers

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Abstract: We present a systematic study of an asymmetric switchable grating enabling the coupling between a waveguide and a ring resonator. The ring can act as an optical memory or as a pulse retiming device.

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1. Introduction

Photonic Integrated Circuits (PICs) represent a promising technology which offers the possibility to combine on a single substrate numerous optical functions including switching, modulation and amplification. Such integration offers new opportunities for optical information processing. Currently, the storage of optical data can only be done by optical-to-electronic conversion. A fast, integrated, all-optical solution that can allow the storage of optical data can strongly enhance the capacity and flexibility of an optical network. Such functionality can be achieved by the use of an asymmetrical grating assisted codirectional coupler (A-GACC)[1, 2] coupled to a ring resonator [3]. Such concept was proposed by Greenberg [4]. In order to broaden the functionality of Greenberg's concept, we suggest the implementation of two switching schemes to the complex grating that would allow either the extraction or the duplication the stored signal. This summary presents a detailed analysis of the optical signal coupled into the ring resonator by using the proposed switchable A-GACC. Lastly, the temporal dynamics of two operating regimes using the switching states of the structure are explored: a memory regime and a pulse-retiming regime.

2. Description of an A-GACC coupled to a ring resonator

The structure of an A-GACC is shown in Fig.1(a).

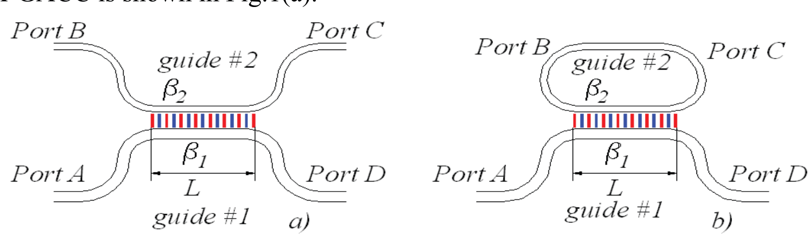

Fig. 1. (a) Asymmetrical-GACC. The complex grating allows the asymmetrical coupling between the two asynchronous guides (labeled as #1 and #2). (b) The ring coupled through the A-GACC.

The two waveguides are asynchronous and their propagation constants are β_1 and β_2 respectively. The signal is injected through Port A in guide #1 and is coupled to guide #2. The coupling is achieved by phase matching the two optical modes with the grating diffractive components. The grating used here is a complex one as shown by Eq. (1). The real and imaginary parts represent the modulation of the refractive index and the gain/loss, respectively.

$$\Delta n \propto \cos\left(\frac{2\pi}{\Lambda}z\right) + jS\sin\left(\frac{2\pi}{\Lambda}z\right), \qquad (1)$$

where Λ is the grating period, and S represents the state of the grating. Three states of interest are considered: S = -1, 0 or +1 which will be called the injection state, the extraction state and the duplication state, respectively. These states of operation assume a plane wave expansion of the signal of the form $\exp[j(\beta z-\omega t)]$. Considering first the injector regime (S = -1), the coupled mode equation theory gives the relationship between the input signals at Port A and B and the output signal at Port C and D:

$$\bar{E}_C = j\bar{E}_A 2\kappa L\,\mathrm{sinc}(\Delta\beta L)\exp\left[j\left(\frac{\beta_1+\beta_2}{2}-\frac{\pi}{\Lambda}+j\alpha\right)L\right]+\bar{E}_B\exp[j(\beta_2+j\alpha)L], \qquad (2)$$
$$\bar{E}_D = \bar{E}_A\exp[j(\beta_1+j\alpha)L],$$

where κ is the coupling coefficient, L is the grating length and α is the propagation loss in the waveguides. The bar over the field E_j means the fields are expressed in the frequency domain. For the sake of simplicity, it is assumed that the losses are the same in both waveguide and within the ring. The asymmetry of the A-GACC coupler is clearly shown by Eq. (2): the signal injected in Port A exits through Port D and is coupled to Port C. On the other hand, the signal injected at Port B does not couple to Port D and exits at Port C. It is also important to note that the signal coupled in guide #2 is amplified even though the imaginary part of the grating gives an average gain/loss of zero. Incorporating the ring structure that links together Port B and C, as it is shown in Fig.1(b), it is clear from Eq. (2) that a signal launched in Port A will be trapped within the ring until it is either extracted by switching the state of the grating or it is completely extinct by the losses, thus demonstrating the memory capability of such a device.

3. Temporal dynamics of an A-GACC coupled to a ring resonator

In order to fully describe the potential of the device shown in Fig. 1(b), it is important to describe the temporal dynamics of pulses coupled inside the ring with respect to the state of the grating. The input pulse train can be described by a series of Gaussian pulses:

$$E_A(t)=\sum_n \exp\left[-(t-nT_r)^2/2t_0^2\right]e^{-j\omega_0(t-nT_r)}, \qquad (3)$$

where T_r is the pulse repetition time, t_0 is the pulse duration and ω_0 is the carrier frequency. Initially, the grating state is set to the injection mode (S=-1) in order to trap the signal within the ring. During this phase of injection, two distinct regimes of interest can be observed: a memory regime and a pulse-retiming regime. The regime in which the device is operated is determined by the relationship between the pulse repetition time and the round trip time inside the ring given by $t_3 = n_{eff2}L/c$ where n_{eff2} is the effective index of guide #2, L_R is the length of the ring including the grating section and c is the speed of light. It is assumed that the pulse duration t_0 is much smaller than the roundtrip time t_3. The memory regime occurs when $T_r << t_3$ while the pulse retiming regime occurs when $T_r \approx t_3$. Once the signal is properly stored in the ring, there are two mechanisms available to get access to the trapped signal. The signal can be retrieved by removing it from the ring by switching the grating state from S = -1 to S = 0 or by duplicating it by switching the grating state from S = -1 to S = +1. The next two subsections will explore the memory and pulse retiming regimes when the signal is duplicated from within the ring.

3.1 Memory regime

When the total duration of the optical signal is less than the roundtrip time, the signal trapped inside the ring will then circulate until it is extracted. The effect of switching the grating from S = -1 to S = +1 basically reverses the asymmetry of the A-GACC. In this situation, the signal in Port B will be then coupled to Port D and Port C. The duplicator state takes its name from the fact that the signal in Port B will be transferred to Port C while being extracted. The output signal at Port D after 4 roundtrips inside the ring is shown at Fig. 2.

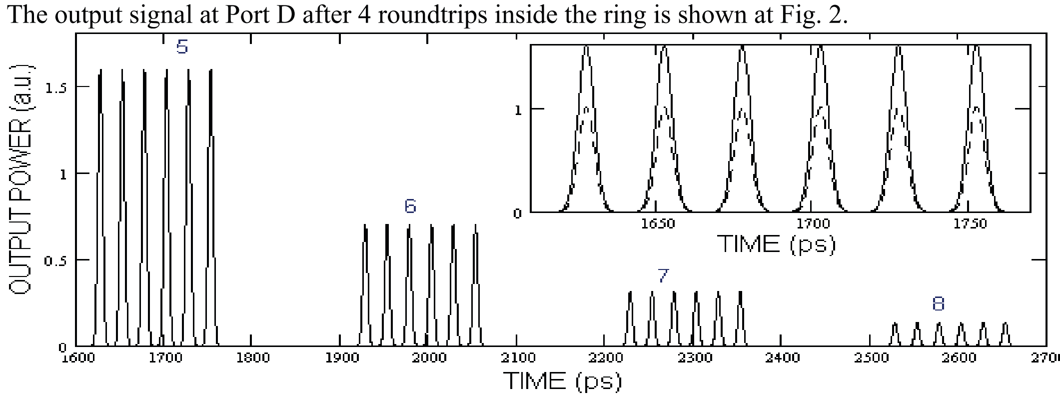

Fig. 2. Signal duplicated from the ring after four roundtrips. The input train contains 6 pulses.

The input signal train (dashed curve in Fig. 2 insert) contains 6 pulses with pulse duration of 3.6 ps spaced by 25 ps. The propagating loss is 6.81 m^{-1}, the length of the ring is 60 mm, the length of the A-GACC is 25 mm, the effective indices are n_{eff1} = 1.519375 and n_{eff2} = 1.5 and the grating strength is $\kappa L = \pi/2$. The grating period is 80 µm, which correspond to a central wavelength of 1.55 µm. One can notice that the output signal is in fact a copy of the input one repeated at an interval corresponding to the roundtrip time inside the ring. It is worth noting each copy is less intense than the previous. When the grating is switched after four full roundtrips, the signal is duplicated in Port D (solid), but it still continues to circulate inside the ring and experience further propagation losses. However, since the injection and the duplication process imply amplification (due to the presence of the imaginary grating), the signal can experience the losses of many roundtrips before its amplitude get lower than the input signal, at it can be seen from the insertion in Fig.2 where the input signal (dash) has been translated temporally for the purpose of comparison with the duplicated signal (solid).

3.2 Pulse retiming regime

Pulse retiming can be achieved with the device shown in Fig. 1b, if the time between the input pulses is slightly lower than the roundtrip time. In this case, the first pulse would couple inside the ring and undergo its first roundtrip. Just before arriving at Port C, another injected pulse from Port A would also be coupled and placed in front of the first one. By carefully adjusting the time between the input pulses, it is then possible to create a new retimed trapped signal inside the ring. An example of such retiming is shown in Fig. 3. The retiming is done for 6 initial pulses. Therefore, six roundtrips are required to retime the whole train inside the ring.

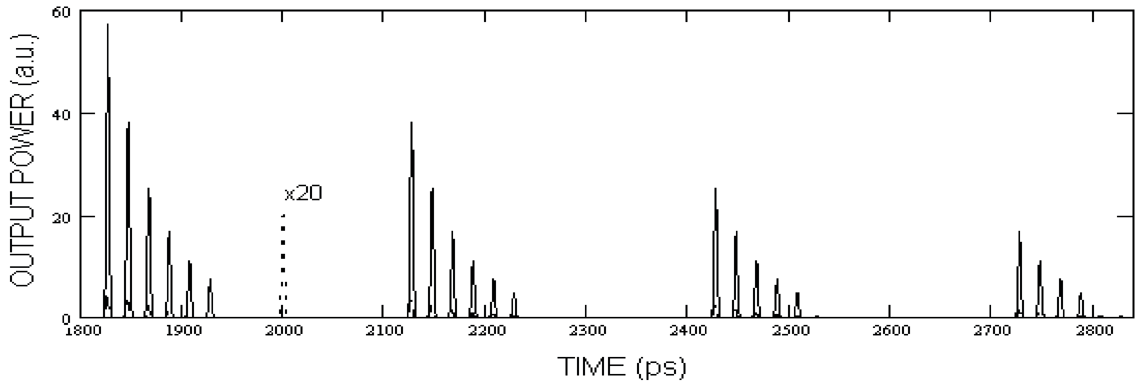

Fig. 3. Retimed signal duplicated into Port D from the ring (solid) and the input signal (dash) multiplied by a factor of 20. Six input pulses are used to achieve the retimed signal train.

The A-GACC parameters used in Fig. 3 are the same as for Fig. 2except that the time between each input pulses is now 280 ps which is less than the roundtrip time t_3 (evaluated to ~300 ps for the ring structure). The propagation losses are 3.4 m^{-1}. One can see that the number of pulses is 6 as expected, although the intensity of each pulses are not the same. This is caused by the fact that each pulse must undergo a roundtrip before receiving a new pulse to the train. Of course, each roundtrip also means more losses, which leads to such pulse train.

4. Conclusion

The investigation of a switchable A-GACC coupled to a ring resonator has been done. Three different grating states have been proposed in order to realize a diverse range of functionalities. These states are: injection, extraction and duplication. Using these configurations, two different regimes of operation have been explored: a memory regime and a pulse-retiming regime. It was shown that the ring can serve as a dynamic memory cell where an optical signal can be efficiently stored. The switchability of the grating gives access to the stored signal for further processing. Furthermore, it was shown that the memory capability also allows the retiming of the pulse. Such functionality leads the creation of signal train with adjustable timing.

5. Acknowledgements

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6. References

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