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On the design of semiconductor optical amplifier-assisted Sagnac interferometer with full data dual output switching capability

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ABSTRACT

The ability of a semiconductor optical amplifier assisted Sagnac interferometer to support error-free as well as pattern-independent operation at both of its output ports simultaneously when all of the incoming data can potentially be switched to them is investigated and demonstrated. For this purpose a numerical model is used to simulate the operation of the considered module so as to identify under which working conditions this full data dual output switching mode is possible. The thorough analysis and interpretation of the results obtained from the evaluation of the impact that each critical parameter has on the defined performance metrics allows to infer that meeting at the limit the criterion for the *Q*-factor at both outputs is determined by the transmission port for all of them but the carrier lifetime, for which the reflection port prevails. However this is not enough to guarantee that the pseudo-eye diagrams acquire their desired form because, although the amplitude modulation is adequate for both cases, the extinction ratio is low. Instead, the achievement of both logically correct and high quality switching demands further refinement of the specified minimum requirements and the selection of the key parameters in such way that the *Q*-factor at the reflection port is optimized. The design rules derived from this procedure can be useful for enabling the implementation of complex all-optical circuits and subsystems that exploit the specific SOA-based interferometric structure as the core building element.

1. Introduction

Over recent years the technology of all-optical switches employing a semiconductor optical amplifier (SOA) as the non-linear element in an interferometric configuration has evolved to the point that it has become essential for efficiently handling ultrafast information only by means of light both in fundamental [1] and system-oriented level [2]. The SOA-assisted Sagnac [3]/Terahertz Optical Asymmetric Demultiplexer [4] has proved its merit in the realization of various signal processing tasks without cumbersome optoelectronic conversions, such as serial Boolean logic [5], wavelength conversion [6], demultiplexing [7], header and payload separation [8] and packet switching [9]. The common characteristic of these photonic circuits and subsystems is that they exploit the product of the switching procedure that emerges at a different terminal from the incoming one (transmission mode [3]), which has affected likewise the trend governing the reported simulation studies [10–16]. On the other hand there are sophisticated applications that also utilize the signal that comes out from the same point from which it was initially launched (reflection mode [3]), as it happens in parallel Boolean logic and arithmetic operations [17], modular arithmetic [18], binary-to-quaternary encoding/decoding [19], buffering [20,21] and multi-valued logic [22]. Therefore it would be desirable to optimize the outcome at the two exits simultaneously so that each can serve its destined functional purpose in the most appropriate way and both can cover as many practical cases as possible. However this goal cannot be directly attained, unless of course a pair of the considered modules is used in parallel, although this is at the cost of extra hardware resources, since the satisfaction of the correct phase conditions is hindered by the form of the corresponding transfer functions. In fact, as it has been explained in [23], the variation of these functions against the phase difference being indispensable for realizing the adopted switching idea [24] is such that it does not allow the process to be carried out in an uncorrelated manner but the proper adjustment of this quantity for one output disturbs the other and vice versa. Moreover, even if the phase requirements are fulfilled, the whole attempt is difficult from a physical perspective due to the fact that the large differential gain required to create the relative phase change for enabling interferometric switching [24] also causes performance degradation [25]. This essentially implies that it is inherently impossible to obtain full constructive interference in the presence of an intense excitation signal, or, equivalently, some useful

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portion of information that should be forwarded to the transmission port will leak to the reflection port. The negative by-product of this disparity is that the binary contents of the pulse streams occurring therein are not mutually complementary, thereby increasing the probability of making logical errors, while their contrast ratio is upper bounded by the SOA linewidth enhancement factor [26]. In order to confront these problems two solutions have been proposed. One intervenes at the interferometer's setup by placing additional phase shifters at the direct path of the targeted outputs [23], which can be independently biased so as to allow the respective phase terms acquire their desired values at the same time. The other tries to maximize the phase-to-gain nonlinearities magnitude by selecting the wavelength of the signal to be switched (clock) to lie at a wavelength transparent to the semiconductor gain region [27], thus strongly suppressing the undesirable pattern dependence but still preserving a sufficient phase shift level. These methods are not without their drawbacks, however, which compromise their benefits in terms of versatility, reconfigurability, scalability and "on-the-fly" processing capability. More specifically, the first is sensitive to the deviations in the phase offset, which hence must be kept within a tight range through electronic stabilization making the adjustment of the setup less flexible, especially in the context of a counter-propagating geometry, like the Sagnac. In the specific module the effective phase shift can alternatively be introduced by inserting in its loop a birefringent element, which nevertheless renders it more vulnerable to variations in the polarization state of the incoming signals. The second in turn has the disadvantage that it cannot be deployed in combinatorial feedback or serial interconnection schemes without wavelength conversion of the switched signal to the spectral region of the signal being responsible for switching (control), which clearly limits its potential for straightforward use in such cases. In addition, at the ultrahigh single channel data rates to which modern lightwave networks are gradually evolving, it is harder to provide the amount of phase shift recommended for proper simultaneous switching [23], as opposed to a conventional employed SOA [28]. Therefore there is a strong motive for making out most of both outputs of the SOA-assisted Sagnac by supporting its design in its standard architecture itself, i.e. without resorting to external assistance or structural modifications as in the measures taken so far. Although there have been reported efforts towards that direction in SOA-based interferometric switches, yet they have been limited to add/drop multiplexing [23], [29–31] where many clock pulses travel through the interferometer but are not acted on by the control so that the performance of the switch may be less sensitive to the SOA dynamics [25]. In contrast this paper aims at extending the pursued scope to the general situation of full data switching, which is a more realistic scenario for the applications of interest [17–22] and may impose a greater strain on the SOA behaviour. For this purpose a theoretical treatment is conducted by means of numerical modelling adapted to the given circumstances to systematically investigate the impact of the critical parameters on the defined performance metrics. This allows to evaluate the restrictions imposed by each output port and find the operational requirements for concurrently supporting error-free and pattern-free switching at both of them. The guidelines derived from the thorough interpretation of the simulation results can be useful for enhancing the multi-tasking competence of the considered type of switch and its pivotal role as signal processing unit.

2. Principle of operation

Fig. 1 depicts the SOA-assisted Sagnac switch considered in this study, which incorporates a SOA displaced from the centre of loop, formed by connecting the branches of a 3 dB coupler, by a distance equivalent to a temporal offset of $T_{asym}/2$. In its classical configuration it is driven by two streams, namely a regular one comprising of continuous logical '1's (clock) and an information-carrying one (control). At the entrance paths of these two beams polarization controllers (PC) are placed, which have a dual role. First, they are used to adjust their polarization vector so that they are both linearly polarized and aligned to the axes of the SOA, the control to the transverse electric (TE) and the clock to the transverse magnetic (TM). This setting has been shown to be necessary [32,33] in order to prevent a possible variation of the SOA gain with the polarization of the launched light (Polarization Dependent Gain—PDG [34]) from causing problems in the switching procedure, as it will described in more detail in the next section. Second, they help discriminate the control from the clock since, by being orthogonal to each other, the former can be inserted and extracted by means of two (polarization) selective couplers (SC) [3] located on either side of the loop, which for this purpose should additionally be constructed from polarization maintaining fiber. The input signals are chosen in such way that only the control is intense enough (at least ten times [4]) to alter the SOA optical properties. These are subsequently suffered by the clock, which is relatively weaker, and can be exploited for the achievement of switching provided the two signals are combined with the appropriate timing conditions. For this purpose a clock pulse enters the setup and is split into two components of equal amplitude, the clockwise (CW) and the counter-clockwise (CCW). After propagating around the loop in opposite direction, they recombine and interfere producing a result at each output port depending on the influence exerted on the SOA gain dynamics by the control. In more detail, and as described in [15], if a control pulse is present, which corresponds to a logical '1', and is synchronized to arrive first at the SOA, then it provokes a fast depletion of the SOA carrier density. Thus the CW copy following just after this perturbation encounters a strongly saturated gain whilst its CCW counterpart that reaches the SOA with a relative delay $2\times(T_{asym}/2)=T_{asym}$ due to its asymmetric position perceives a partially recovered gain.

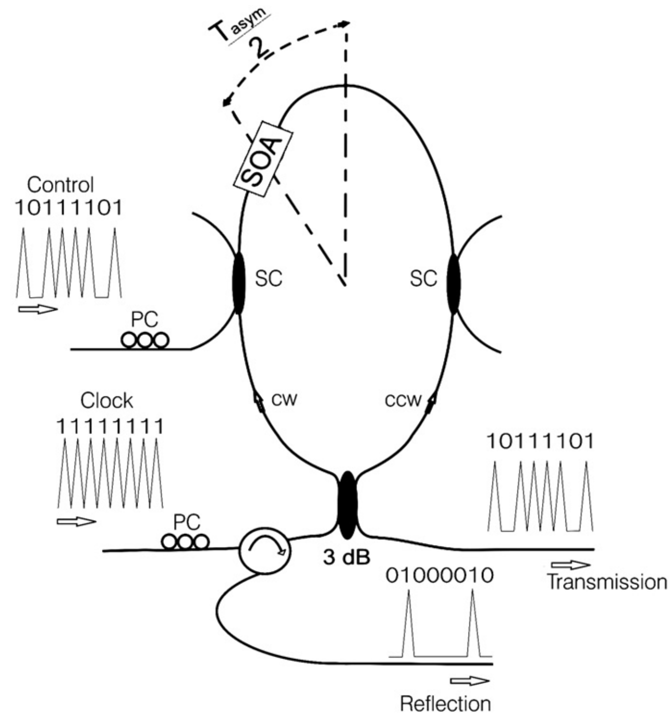

Fig. 1. SOA-assisted Sagnac switch configuration under study.