Investigation of SOA-assisted Sagnac recirculating shift register switching characteristics

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Abstract

The switching characteristics of a Semiconductor Optical Amplifier (SOA)-assisted Sagnac recirculating shift register with an inverter are investigated by undertaking a numerical analysis that describes the dynamic gain response of the SOA to high speed and strong feedback optical pulses. The key performance parameters are identified and their role in the formation of the switching window is analyzed. The optimum values of these parameters are not unique and must be adapted to the specific all-optical shift register network application. For this reason, they must be properly selected and combined so as to ensure the satisfaction of the desired operating conditions. The technical restrictions that the derived values may impose on the state-of-the-art photonics technology are also discussed and efficient ways of overcoming them are proposed.

Keywords: All-optical recirculating shift register; All-optical signal processing; Semiconductor optical amplifier (SOA); SOA-assisted Sagnac switch; Switching window

1. Introduction

The unceasing bandwidth demand that is fuelled by the massive use of Internet and multimedia applications has spurred the development of ultrafast all-optical networks capable of offering large traffic capacities and supporting high-quality integrated services [1]. The main characteristic of these networks is that information remains exclusively in the optical domain along the communications path without opto-electrical (O/E) and electro-optical (E/O) conversions but only inevitably at

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electronic circuits. Furthermore, it can facilitate packet header recognition by buffering an incoming packet while its header is processed to investigate if it matches a local address and to determine how it must be routed. Moreover, it can be placed in routers to queue incoming packets before their turn for switching arrives so as to avoid packet contentions and destination conflicts at the routing ports. It can play also a role equivalent to electronic shift registers as buffer for further processing of the data streams derived from the performance of all-optical Boolean logic functions. Finally, it can find application in the development of non-trivial complex all-optical circuits of enhanced functionality [5], such as an all-optical pseudo-random binary sequence generator and an all-optical error counter, which in turn can be exploited for the demonstration of a high-speed, all-optical Bit Error Rate Tester.

Due to their multitasking capability and key role as network elements, all-optical shift registers have attracted considerable research interest. Among the various all-optical shift register implementations, those that use a Semiconductor Optical Amplifier (SOA) and in particular in an interferometric configuration are very promising for several reasons. Firstly, they are characterized by the attractive features of fast switching time, high repetition rate, low power consumption, noise and jitter tolerance, compactness, thermal stability and high non-linear properties, which enable their efficient exploitation in a real ultra-high speed optical communications environment [6]. Secondly, they have the potential of being integrated, which in turn means that they can be repeatably and reliably manufactured and massively produced so that they can be of commercial value and favorably compete with other buffering solutions [7]. Thirdly, they are operationally versatile, which means that they can be exploited in more complex all-optical signal-processing applications without significantly changing their fundamental architecture [8]. Finally, the storage/buffering time can be altered at will by simply adding or removing fiber without significant cost in power dissipation or energy loss [9].

In this paper, we investigate the switching characteristics of a regenerative, recirculating optical shift register with an inverter architecture that employs a SOA-assisted Sagnac switch [10]/Terahertz Optical Asymmetric Demultiplexer [11]. Although a model simulating this circuit has been presented [12,13], it focused mainly on explaining and getting a deeper insight on its behavior by defining two modes of operation rather than exploring the dependence on its critical operational parameters. It would be useful thus to investigate in an extensive and systematic manner how the performance of this circuit, that is governed by factors such as the SOA small signal gain and carrier lifetime, the switching pulses energy and width and the Sagnac loop asymmetry, can be improved and optimized. In order to achieve this goal, a model is developed that describes propagation and amplification of optical pulses through a SOA in an interferometric switch as well as the interaction of the SOA carriers with an intense optical field and is appropriately applied to the case of the specific shift register operating at 10 GHz. The model is then numerically solved to derive the switching window, which is the ultimate performance evaluation metric of an all-optical interferometric configuration [14], and study the influence of the critical parameters on its width and contrast so as to extract the conditions under which these two characteristics become optimum. The validity of the model is proved through comparison of the simulated switching window against the available experimental one that reveals good agreement. This essentially implies that it can also be exploited to thoroughly analyze other more complex all-optical signal-processing circuits that employ semiconductor-based all-optical shift registers as the basic building block, particularly in applications where more than one feedback path may exist [15].

2. Principle of operation

The operation of the recirculating shift register can be better described with the help of the simplified block diagram of Fig. 1, which consists of a SOA-assisted Sagnac switch arranged in such a way that its output drives its input. The switch consists of an optical loop mirror formed by the joined output ports of a 2 × 2 3 dB coupler and a SOA that is offset from the midpoint of the loop as the non-linear element. A clock pulse that can be provided by a pulsed laser (either a gain-switched DFB or a mode-locked ring laser) enters the loop through the input port of the 3 dB coupler and is split into two counter-propagating pulses, the clockwise (CW) and counter-clockwise (CCW), of equal amplitudes and identical phases. The power of the clock signal is small enough so that it does not affect the optical properties of the SOA. In the absence thus of control/
switching pulses, the dynamics of the SOA remain unchanged and consequently its action is the same on the two conjugate pulses when they pass through. In that case no phase difference is created between both pulses and the whole configuration operates as a symmetric loop mirror resulting in the reflection of the recombined clock signal at the corresponding coupler port. The reflected signal is then appropriately amplified by an optical amplifier to obtain an energy of at least ten times higher than that of the inserted clock signal \(^{[16]}\) and is fed back to the switch as control signal. This amplifier can be either an EDFA \(^{[11]}\), which results in large physical size of the shift register and consequently inhibits integration and impedes “on-the-fly” signal processing, or preferably a SOA \(^{[10]}\), which due to its compact size can minimize the time-of-flight of the switch and ensure reasonable access times to recirculating information. The control and clock signals can be discriminated by appropriately adjusting their polarization states so that they are orthogonal to each other. This enables also the insertion and extraction of the control signal in and from the loop using two polarization selective couplers, PSC1 and PSC2, respectively, and at the same time eliminates the need for complex wavelength conversion that would be otherwise required \(^{[17]}\). Provided that the injected strong control pulses are appropriately timed with respect to the clock pulses, they can alter the SOA carrier density and greatly change its refractive index. Since the SOA is asymmetrically placed in the loop, the counter-propagating clock pulses reach it with relative delay and so experience different dynamic states. As a result, the two components suffer a different gain, which in turn induces a different phase shift between them so that when they recombine at the coupler switching can occur at the transmission port.

The use of the reflection port for feedback inevitably causes the inversion of the logical value of the inserted pulses so that the temporal output at the transmission port of the shift register consists of alternating blocks of “1” and “0”. The period of each block is

\[
T_D = L \cdot (n/c)
\]

(1)
time units, where \(L\) is the total length of the Sagnac loop and the feedback path, \(c\) the speed of light in vacuum and \(n\) the refractive index in fiber. In other words, \(T_D\) is the memory storage time and is equivalent to the number of bits, \(m\), that are contained inside the total length, \(L\), multiplied by the period of each bit, \(T_{\text{bit}}\).

\[
T_D = m \cdot T_{\text{bit}}.
\]

(2)
The number of bits, \(m\), that are contained in the memory, essentially corresponds to the delay elements (flip-flops) created by the physical length of the fiber as pulses travel it and is also a measure of the total capacity of the memory. In this sense and in order also to ensure pulse synchronization within the shift register, \(m\) must be an integer number, which can be achieved by appropriately adjusting the total round-trip delay of the switch and the feedback path. In the experimental demonstration in \(^{[10]}\), for example, the transit time through the switch and feedback path was 606 ns, which corresponds from (2) to a memory capacity, \(m\), of 6061 electronic equivalent flip-flops.

### 3. Model formulation

In this section, we develop a comprehensive theoretical model based on the SOA gain dynamics to simulate the shift register’s operation according to the description of the previous section.

The analysis starts from the following basic interferometric equations that describe the output signal at the transmission and reflection port \(^{[18]}\),

\[
T(t) = 1/4 \left\{ G_{\text{CW}}(t) + G_{\text{CCW}}(t) - 2 \sqrt{G_{\text{CW}}(t)G_{\text{CCW}}(t)} \times \cos[\phi_{\text{CW}}(t) - \phi_{\text{CCW}}(t)] \right\}
\]

(3)
and

\[
R(t) = 1/4 \left\{ G_{\text{CW}}(t) + G_{\text{CCW}}(t) + 2 \sqrt{G_{\text{CW}}(t)G_{\text{CCW}}(t)} \times \cos[\phi_{\text{CW}}(t) - \phi_{\text{CCW}}(t)] \right\}
\]

(4)
respectively, where \(G_{\text{CW(CCW)}}(t)\) is the SOA gain seen by the CW (CCW) pulse and \(\phi_{\text{CW(CCW)}}(t)\) the corresponding phase shift. These two parameters are related to each other by

\[
\phi_{\text{CW}}(t) - \phi_{\text{CCW}}(t) = - \frac{\pi}{2} \ln \left( \frac{G_{\text{CW}}(t)}{G_{\text{CCW}}(t)} \right),
\]

(5)
where \(z\) is the SOA linewidth enhancement factor.

From (3)–(5) it can be seen that the calculation of \(T(t)\) and \(R(t)\) requires the knowledge of the gain \(G_{\text{CW(CCW)}}(t)\). For this purpose, the equations that describe pulse propagation in a SOA as well as the SOA carrier response to an injected optical field are appropriately combined and applied for each pulse (CW and CCW) according to the operation principle of the shift register. This approach results in a system of partial differential equations over the temporal and longitudinal variables that characterize the pulse shape and SOA length \(^{[19]}\), respectively, which inevitably increases the computational complexity of the theoretical model. This problem can be overcome by using a time-dependent power gain coefficient integrated over the SOA space variable \(z\), \(\bar{g}(t)\), that takes implicitly into account the variation of the gain coefficient, \(g\), along its length, \(L\), \(^{[20]}\).

\[
\bar{g}(t) = \int_0^L g(z, t) \, dz.
\]

(6)
In this way, the dependence on the spatial variable can be dropped and the two-dimensional system of differential equations reduces to the following ordinary differential equation that under certain approximations can be solved analytically:

$$\frac{dh(t)}{dt} = g_{ss} L - h(t) \frac{1}{\tau_{\text{car}}} - \frac{c n_g \bar{A}}{2} \frac{U_{\text{in}}(t)}{U_{\text{sat}}} \{ \exp [h(t)] - 1 \}. \tag{7}$$

In this equation, the only variable is the local time $t$ in the retarded reference frame moving with the pulse that is obtained through the transformation $\tau \rightarrow \tau - z / u_g$, where $u_g$ is the group velocity [20]. Furthermore, $g_{ss} = \Gamma z_N N_{1r}(I / I_{tr} - 1)$ is the small signal gain coefficient per unit length when the SOA internal loss is neglected, where $\Gamma$ is the confinement factor, $z_N$ is the differential gain, $N_{1r}$ and $I_{tr}$ are the carrier density and injection current required for transparency, respectively, with $g$ being the electron charge, $\tau_{\text{car}}$ the carrier lifetime and $V = w d L$ the volume of the active region, with $w$ and $d$ being the corresponding width and depth. Also $n_g$ is the group index of refraction, $\bar{e}_0$ is the dielectric constant in vacuum, $A$ is the cross-sectional area of the active region that equals $w d / \Gamma$, $P_{\text{in}}$ the input power and $U_{\text{sat}}$ the saturation energy of the amplifier

$$U_{\text{sat}} = h \bar{e}_0 A / z_N, \tag{8}$$

where $h \bar{e}_0$ is the photon energy and for typical values $d = 250 \text{ nm}$, $w = 2 \mu m$, $\Gamma = 0.48$, $z_N = 3.3 \times 10^{-20} \text{ m}^2$, $n_g = 3.62$ at an operating wavelength $\lambda = 1550 \text{ nm}$ equals approximately $1000 \Omega$.

In deriving Eq. (7), the contribution of SOA intraband processes, such as carrier heating and spectral hole burning [21] that can be included in the description of its gain dynamics under pulsed operation by using the corresponding non-linear gain compression factors [22,23], is neglected, since these effects become important for pulses shorter than 2 ps [22,24], which is not the case, however, in this model where pulses longer than this critical value are only considered. It must be also noted that the performance of the configuration in Fig. 1 can be limited by the presence of noise (amplified spontaneous emission – ASE) that is inserted in the shift register circuit from the SOA in the loop and the feedback path and accumulates in each pulse recirculation. However, this problem is resolved by using a technique that exploits the SOA in the feedback path not only for amplification, but also to provide a reflected signal as noise-free as possible [10]. This is necessary in order to avoid the strong saturation of the SOA in the loop and the degradation of the switching performance. For this purpose, a clean signal that is provided by a clock source is inserted to this SOA whose gain is modulated by the “1” and “0” in the reflected signal. This second SOA of the shift register circuit acts thus as an encoder that maps the noisy reflected signal to the noise-free clock signal, essentially isolating the control signal that is inserted in the switch through the feedback path from the directly reflected signal. In this manner, most of ASE can be removed, while any remaining part has relatively less power compared to the control signal that enters the loop, so that it cannot alter in an undesired way the gain dynamics of the intraloop SOA. Since the developed model aims at simulating the experimental setup in [10], which in turn relies on this approach that essentially enables to eliminate ASE so that its influence on the shift register performance is negligible, it is reasonable and acceptable to neglect also ASE in the simulation equations, without affecting the accuracy of the obtained results and the main conclusions drawn for the proper selection of the critical parameters.

Eq. (7) forms the basis for calculating the SOA impulse response, $h(t)$, that is subsequently used to describe the SOA gain response features. This is separately done for the gain rapid saturation and slow recovery regions, as it is described in the following subsections, respectively.

### 3.1. Gain saturation by a short optical pulse

The gain saturation of the SOA can be analytically described if it is assumed that the width of the incoming pulses is much lower than the carrier lifetime of the amplifier [20] so that the gain has no time to recover during pulse duration. This in turn means that the first term in the right-hand side of (7), which is proportional to $1 / \tau_{\text{car}}$, can be neglected with a good approximation, because the spontaneous recombination and carrier injection are too slow to respond within the pulse interval to the change of carrier density caused by the stimulated emission. This assumption is justified in the case of the developed model since pulses have a full-width at half-maximum (FWHM) of a few picoseconds (ps), while the typical values of the carrier lifetime are of the order of several hundreds of ps. The solution of (7) is thus

$$h(t) = - \ln \left[ 1 - \left( 1 - \frac{1}{G_{\infty}} \right) \exp \left( - \frac{U_{\text{in}}(t)}{U_{\text{sat}}} \right) \right], \tag{9}$$

where

$$U_{\text{in}}(t) = \frac{c n_g \bar{e}_0 A}{2} \int_0^\infty P_{\text{in}}(t') \, dt' \tag{10}$$

is the energy fraction contained in the leading edge of the control pulse until the moment $t < t'$. By definition $U_{\text{in}}(t \to \infty) = U_p$, where $U_p$ is the total energy of the pulse inserted in the SOA. The instantaneous SOA gain,

$$G(t) = \frac{P_{\text{out}}(t)}{P_{\text{in}}(t)},$$

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is given from
\[
G(t) = \exp[h(t)] = \left(1 - (1 - G_{ss})\exp(-U_{in}(t)/U_{sat})\right)^{-1}.
\]
(11)

The parameter \(G_{ss}\) is the SOA small signal gain seen by the leading edge of the pulse as it is inserted in the unsaturated SOA and whose value, which equals \(\exp(g_{ss}L)\) when the SOA internal losses are neglected for simplicity, can be varied by changing the injection current. The gain seen by the trailing edge of the pulse is obtained from (11) letting \(t \to \infty\) and is essentially the final gain reached at the saturation level to which the SOA is brought
\[
G_f = G(t \to \infty) = \frac{G_{ss}}{G_{ss} - (G_{ss} - 1)\exp(-U_p/U_{sat})}.
\]
(12)

This equation has the physical meaning that as the intense control pulse travels through the SOA, it provokes a rapid depletion of the available carriers in the active region that are provided by the injection current, which is directly followed by a decrease of the gain from the initial and high small signal value to the final and smaller saturated value.

### 3.2. Gain recovery

After the SOA is saturated to a final value according to (12), the action of the control stops and so the gain begins to recover slowly, due to the injection of carriers by the corresponding current, with a time constant \(\tau_{car}\). The absence of the control can be thus mathematically expressed by setting in (7) \(P_{in} = 0\), so that the stimulated recombination term (second term) in the right-hand side of (7) diminishes resulting in
\[
\frac{dh(t)}{dt} = g_{ss}L - h(t)/\tau_{car},
\]
(13)

with solution
\[
h(t) = B\exp(-t/\tau_{car}) + g_{ss}L.
\]
(14)

The constant \(B\) can be found if the appropriate initial temporal conditions are satisfied. This can be achieved by realizing that the response of the SOA to the control pulse sequence is different from that to a single pulse and is related to the pulse repetition period, which in ultrafast all-optical signal applications like the shift register is less than the SOA carrier lifetime. This results in an incomplete recovery between the continuously inserted pulses, so that the SOA gain has not enough time to return to the small signal value, \(G_{ss}\), but instead to a smaller gain value, \(G_0\), which approaches asymptotically \(G_{ss}\) as \(t \to \infty\), while at time \(t_s\) it has reached the saturated, final gain \(G_f\). With these conditions, the expression for the SOA gain recovery is obtained finally from (14)
\[
G(t) = \exp[h(t)] = \frac{G_f}{G_{ss}}\exp[-(t-t_s)/\tau_{car}], \quad t \geq t_s.
\]
(15)

### 3.3. Application to SOA-assisted Sagnac recirculating shift register with an inverter

The results obtained for the SOA gain saturation and recovery regions are applied now to the case of a SOA-assisted Sagnac recirculating shift register with an inverter that receives a train of clock pulses.

According to the description in Section 2, the first clock pulse is inserted in the loop but since there is no control pulse present, its counter-propagating components exhibit an equal, unsaturated SOA gain so that \(G_{CW} = G_{CCW} = G_{ss}\) and hence, from (5), no phase difference occurs, i.e. \(\phi_{CW} - \phi_{CCW} = 0\). This pulse is thus totally reflected by the switch and its power is from (4)
\[
P_{out}(t) = R(t)P_{in}(t) = G_{ss}P_{in}(t)
\]
(16)

where the shape of the input optical clock pulses is assumed to be Gaussian with power
\[
P_{in}(t) = \frac{U_p}{\tau_0\sqrt{\pi}}\exp\left(-\frac{t^2}{\tau_0^2}\right).
\]
(17)

In this equation \(\tau_0\) is related to the FWHM by \(\tau_p \approx 1.665\tau_0\) [20].

The first reflected pulse is then appropriately amplified and fed back in the circuit to act as control/switching pulse but since the propagation delay that is inserted by the loop and the feedback path must be such that, according to (2), \(m\) pulses are contained inside the memory, this means that it takes \(m\) pulses before the control pulse that corresponds to the first reflected pulse arrives at PSC1. This control pulse transits thus the loop together with the \(m+1\) input clock pulse to which it induces a phase shift equal to \(\pi\) so that it can be switched at the transmission port. In a similar way, the pulses between \(m+1\) and \(2m\) are transmitted by the switch and no reflected pulses are generated. The \(2m+1\) pulse transits again the loop without a control pulse present and so it is reflected forming once again the new control pulse. In this manner and depending on the pulse number, switching and unswitching regions are formed between which the shift register reverts periodically, as shown in Fig. 2. Since, we are primarily interested in simulating the operation of the shift register while being in the switching region, the involved functions that describe in the following the control pulses total energy and the SOA gain variation should have a subscript to underline the fact that only pulses that lie within this region, namely pulses between \(m+1\)
and 2m, 3m + 1 and 4m, and so on, are considered. This subscript is, however, implied and omitted for convenience and simplicity of presentation.

According to the previous description, the input CW clock pulse enters the SOA together with the control, reflected pulse but as it has much less energy (at least 10 times as mentioned in Section 2), it cannot saturate the SOA and its leading edge sees an initial, unsaturated gain. Since a periodic train of pulses is inserted in the SOA and not just one pulse, this means that a quasi-saturating state is quickly established so that it is impossible for the SOA gain to reach the small signal saturating state is quickly established so that it is impossible for the SOA gain to reach the small signal gain value, $G_{ss}$, but instead a smaller one, $G_0$, so that $G_{CCW} = G_0$. As the control pulse transits thus the SOA, the gain reduces from $G_0$ to a final saturated gain $G_f$, seen by the trailing edge of the pulse, according to (11), which is modified by replacing $G_{ss}$ with $G_0$ and, from (10), (16) and (17), $U_{in}(t)$ with

$$U_{out}(t) = \frac{1}{2} U_{tot}[1 + \text{erf}(t/\tau_0)],$$

where erf(·) is the error function and $U_{tot} = G_{ss}U_p$, so that

$$G(t) = \left\{ 1 - (1 - 1/G_0) \exp \left[ -\frac{U_{out}(t)}{U_{sat}} \right] \right\}^{-1}. \quad (19)$$

The SOA saturation time, $t_s$, is practically equal to the control pulse width, $\tau_p$, because if the time $t$ in (18) is replaced with $\tau_p$, then $U_{out}(t) \approx 99\% U_{tot}$, or in other words, 99% of the control pulse has transit the SOA. Using thus $t_s = \tau_p$ in (19), the final gain can be obtained

$$G_f = G(t_s) = \frac{G_0}{G_0 - (G_0 - 1) \exp(-U_{tot}/U_{sat})}. \quad (20)$$

After the CW pulse transit and the SOA saturation by the control pulse, the CCW pulses that arrives with a delay equal to the asymmetry, $\tau_{asym}$, sees from (15) a gain

$$G_{CCW} = G_{ss} \left[ \frac{G_f}{G_{ss}} \right]^{\exp\left[-(\tau_{asym}-\tau_p)/\tau_{car}\right]}, \quad t \geq t_s. \quad (21)$$

After one time period, $T_C$, the SOA gain has not reached $G_{ss}$ but $G_0$, because the clock and control pulses arrive faster than the SOA carrier lifetime and thus

$$G_0 = G_{ss} \left[ \frac{G_f}{G_{ss}} \right]^{\exp\left[-(T_C-\tau_p)/\tau_{car}\right]}, \quad t \geq t_s. \quad (22)$$

With the arrival of the next CW pulse, the gain starts reducing again and the same process is repeated for the rest of the incoming clock pulses that lie within the switching region.

In order to calculate $G_{CCW}$ and $G_{CCW}$ it is necessary to know $G_0$ and $G_f$. This can be achieved by replacing $G_f$ from (20) in (22) and solving the transcendental equation that occurs recursively for $G_0$ in terms of $G_{ss}$, $T_C$, $\tau_p$, $\tau_{asym}$, $\tau_{car}$ and $U_{tot}/U_{sat}$ (or equivalently $U_p/U_{sat}$). The solution is substituted then in (20) to calculate $G_f$, which together with $G_0$ allows to find the gains of the CW and CCW pulses from $G_{CCW} = G_0$ and (21), respectively, as well as the phase shift from (5) for given values of $\alpha$. Finally, the obtained gains and phase shifts are replaced in (3) and (4) to calculate $T(t)$ and $R(t)$, respectively.

4. Results and discussion

4.1. SOA dynamic gain response

Given the central role of the SOA in the operation of the SOA-assisted Sagnac shift register and before applying the results obtained in Section 3 to the simulation of the shift register, it is important to investigate and understand first the SOA dynamical behavior with respect to several critical operational parameters, such as the control pulse energy and width and the SOA small signal gain and carrier lifetime. This can be achieved if Eqs. (11), (12) and (15) are used, assuming a Gaussian pulse profile so that $U_{out}(t) = \frac{1}{2}U_{tot}[1 + \text{erf}(t/\tau_0)]$, to plot the variation of the instantaneous gain in the saturation and recovery regions against the mentioned parameters. This task is performed for simplicity for a single pulse only but the qualitative results apply also for the case of a pulse train.

Figs. 3 and 4 show the SOA dynamic gain response to control pulses of different energy and width, respectively. From Fig. 3 it can be seen that when there is no control pulse injection or its energy is small enough (less than 10% of the SOA saturation energy [16]), the gain is equal to the small signal value. However an intense control pulse is inserted in the SOA, the gain decreases rapidly and becomes minimum at the final saturation.
point, which is reached when the whole pulse energy has passed by. The gain recovers then slowly in time. The larger is the control pulse energy, the deeper is the SOA saturation and the steeper is the gain curve, which is highly desirable in order to impart a differential phase as close as \( \pi \) between the counter-propagating clock pulses and achieve full switching. Fig. 4 shows that the dynamic gain response is also significantly affected for control pulses having the same energy but different widths. More specifically, the decrease of the pulse width results in a steeper gain transition from the initial small signal to the final saturation value. This happens because a shorter pulse enhances the rapid depletion of carriers and passes quickly through the SOA, in contrast to a longer pulse that needs more time to traverse the SOA and cause a change in its optical properties.

The influence of the small signal gain on the SOA dynamic response is depicted in Fig. 5 and as it can be clearly seen, for specific pulse energy and width the change of the gain is more significant as the value of this parameter becomes higher. This suggests that a large gain would be preferable in order to create the desired differential gain and hence phase difference between the counter-propagating clock components. At the same time this would enable the reduction of the required pulse energy, which is an attractive feature from a practical point of view since it can be provided from commercially available optical amplifiers. As it will be described in the following subsection, however, a very high small signal gain can lead to phase changes greater than \( \pi \) that result in the distortion of the output pulses and the degradation of the switching performance. On the contrary, a decreased small signal gain results in a gain variation far away from heavy saturation that can be compensated for by increasing the pulse energy, as described in Fig. 3, but with negative impact on the cost and complexity of the feedback optical amplifier. There is thus a trade-off between the small signal gain and the pulse energy in order to ensure optimum operating conditions.

Finally, the dependence on the spontaneous carrier lifetime is illustrated in Fig. 6. This parameter determines critically the duration of gain recovery, which in turn affects the gain suffered by the counter-propagating
clock pulses as well as the induced phase difference between them and hence the quality of switching. As the carrier lifetime increases, it takes more time for the gain to recover and the gain curve tilts towards the horizontal axis. For ultra-high speed all-optical shift register applications, the carrier lifetime must be significantly reduced so that the SOA can handle properly the pulses that arrive more often. However, this cannot be achieved by simply varying the driving current or using a longer SOA [25], as it will be explained in more detail in the following subsection.

4.2. Switching characteristics of SOA-assisted
Sagnac recirculating shift register with an inverter

The results obtained in the previous subsection for the SOA dynamic gain response are exploited now to characterize the switching window of the SOA-assisted Sagnac recirculating shift register with an inverter. This is a performance metric that provides valuable information regarding the shape, amplitude and temporal width of the optical transfer function of the all-optical circuit. This window is opened by the fast change of the SOA optical properties provoked from the strong control pulse and their subsequent recovery. In order to achieve thus switching, the clock pulses must be contained within this window, which ideally must be characterized by a sharp edge on its rising and falling sides. The width of this window is approximately equal to the time difference in the arrival of the counter-propagating clock pulses at the SOA, which is twice the temporal offset of the SOA from the fiber loop center [16], and can be practically altered by using an optical delay line inside the loop. Furthermore, this width essentially determines the maximum aggregate data rate that the shift register can support [8], which implies that if the shift register must be capable of storing ultra-high speed all-optical information, a narrow switching window is required. At the same time, a short switching window is necessary in order to store each single bit of a data stream, which may be, for example, the outcome of the XOR comparison with a local address [26], for further processing in an error counter circuit [5]. This, however, does not guarantee the best operational conditions, because if the switching window is too narrow, a possible timing jitter in the incoming information will be transformed into intensity noise at the output resulting in an increase of the bit error rate and in performance degradation [23]. On the other hand, a wide switching window is required to store an entire packet [27] and also to increase the timing jitter tolerance so as to enable regeneration of the recirculating pulses [17]. This widening can, however, increase the gain difference outside the switching window and hence the signal leakage from the transmission port, which is therefore undesirable for feedback applications like the shift register. The selection of the switching window width depends thus decisively on the specific application of the shift register, while its optimization in order to ensure the best performance is not a trivial task. This is due to the fact that the switching window is heavily dependent on the actual operational conditions, which in turn are influenced by several critical parameters, such as the control pulse energy and width, the SOA small signal gain and carrier lifetime and the loop asymmetry.

Concerning also the amplitude of the switching window, this can be actually described by the contrast ratio, which is the signal ratio between the on-off states of the switch at its two output ports, i.e. $T/R$. This must ideally be as high as possible so that the largest fraction of the incoming clock signal exits at the transmission and not at the reflection port. By dividing (3) and (4) for a $\pi$ phase change ($\phi_{CCW} - \phi_{CW} = \pi$) it is obtained

$$T = \frac{(G_{CW} + G_{CCW} + 2\sqrt{G_{CW}G_{CCW}})}{(G_{CW} + G_{CCW} - 2\sqrt{G_{CW}G_{CCW}})}$$

and substituting $G_{CCW}/G_{CW} = 0.35$, which is derived from (5) for a typical value $c = 6$, the contrast ratio can be calculated to be approximately 12 dB (15.8), which is the upper limit of the amplitude of the switching window in the obtained curves. Here it must be noted that in the case of a counter-propagating pulse interferometric geometry, like the SOA-assisted Sagnac switch, the SOA finite length can become a limiting factor concerning the switching window characteristics, especially as the control pulse width or asymmetry values approach the SOA transit time. However, this effect has been investigated in detail elsewhere [28] and is not taken into account in the developed model. This is also justified by the fact that the equations it consists of are solved using the amplification function of (6), which eliminates the spatial dependence. The results presented in the following focus thus on examining the influence of the rest of the critical involved parameters on the switching window.

In order to numerically simulate and calculate the switching window, the time that elapses between the control and the CW clock pulses entering the loop is intentionally varied. This can be mathematically described by

$$P_{out}(t) = \frac{U_{10}}{\tau_0 \sqrt{\pi}} \exp\left[-\frac{(t-t_0)^2}{\tau_0^2}\right].$$

In this equation, which essentially expresses the control input power, the parameter $t_0$ can be varied between positive and negative values of the operating period. Physically, a positive value means thus that the control
pulses are \( t_d \) time units behind the clock pulses, while a negative value corresponds to an advance by the same amount of time.

According to the definition for the energy in (10), Eq. (24) implies that

\[
U_{\text{out}}(t) = \frac{1}{2} U_{\text{tot}} \left( 1 + \text{erf} \left( \frac{t - t_d}{\tau_0} \right) \right).
\]

Using the same rational for the SOA saturation time, \( t_s \), as in (18), it can be deduced that in the case of (25) \( t_s - t_d = \tau_p \Rightarrow t_s = t_d + \tau_p \), so that in a similar way 99% of the control pulse has transit the SOA.

Before proceeding with the analysis, it is necessary to specify the range of permissible values that the asymmetry can take. This is due to the fact that this parameter essentially determines the width of the switching window and hence the performance of the shift register. In order to achieve thus optimum operation, the asymmetry must be less than half the clock bit period, \( T_c \), otherwise the two counter-propagating halves of the pulse being processed by the switch will not follow each other inside the SOA resulting in incomplete switching. An additional requirement for a pulse to be fully transmitted is that its width, \( \tau_p \), must be as short as possible and ideally less than the asymmetry so that when the CCW pulse is inserted in the SOA, the CW pulse has already passed through and the SOA gain has started recovering after saturation by the control pulse. This in turn implies that the width of the switching window cannot be shorter than the control pulse width [29]. Moreover, the asymmetry must be less than the gain carrier lifetime, \( \tau_{\text{car}} \), so that the CCW pulse enters the SOA before carrier recombination is completed in order to experience a decreased gain and acquire the required phase shift. The simultaneous satisfaction of all these conditions is expressed as

\[
\tau_p < \tau_{\text{asym}} < T_c/2 < \tau_{\text{car}},
\]

which essentially defines the range of permissible values that the asymmetry can take.

The switching characteristics of the shift register are plotted in Figs. 7–11, in which the output at the transmission port is calculated as a function of the time delay between the CW clock pulse and the control pulse for different operational conditions. The variation of this temporal separation effectively changes both output ports of the interferometer, since when the clock pulse goes far beyond or behind the control pulse, these is no output at the transmission port and only when the time delay varies in a certain range there is output at the same port. A switching window is thus created between the input and output of the shift register circuit. The curves were obtained by scanning through each involved parameter, while keeping constant the others to a fixed value, and this process was repeated until all parameters were covered. These fixed values were selected in accordance to the experimental ones [10] and namely are: (a) for the small signal gain, 20 dB, (b) for the switching pulse energy, 100 fJ, (c) for the control pulse width, 12 ps, (d) for the carrier lifetime, 100 ps and (e) for the asymmetry, 30 ps.
Fig. 7 illustrates the effect on the switching window for different small signal gain values, which are all over 10 dB. This lower limit can be obtained by recalling that the control energy must be at least 10 times higher than that of the clock, which means that $U_{\text{tot}} = G_{ss}U_p \geq 10U_p$ or $G_{ss} \geq 10$. The curve obtained at 10 GHz enables to assess first the validity of the model by comparing it against the experimental one [26]. Since the experimental pulses had a width of 12 ps, the created window must be flat and high for a duration that is at least equal to this value so as to guarantee an adequate switching performance. The numerical results show that this condition is satisfied for a time interval of 16 ps. Although in that case the control pulses are contained within the switching window, as it is required according to the principle of operation of the Sagnac switch, at the same time its size is small compared to the 12 pulses, which justifies the obtained moderate contrast ratio [26] and extinction ratio [10]. It must be noted, however, that unlike the theoretical prediction, the shape of the experimental switching window in [26] was asymmetric.

This discrepancy is attributed to the SOA finite length that determines the propagation time of the pulses and, as it was mentioned, limits the minimum achievable width of the switching window. More specifically, the leading part of the switching window had a rise time of several ps, partially because the experimental measurement convolved the transmission function with the 12 ps pulses. There was, however, an additional time region attached to the trailing part that equalled 22 ps, i.e. twice the transit time for a 1000 μm long SOA, in accordance with other reported results [30]. In other words, the rise and fall time of the switching window were determined by the width of the control pulses and were limited by the length of the SOA, respectively [31]. Moreover, there was a floor outside the main switching window, which originated from the experimental conditions and could be attributed, for example, to an imperfect input 3 dB coupler or to the pedestal that was inevitably present at the gain-switched output pulses of the frequency doubler used in the experiment. Furthermore, the shift of the theoretical window towards the left-hand side of the time axis compared to the experimental one is exactly due to the fact that the SOA is considered as a point. From the observation of Fig. 7 it can be also seen that there is an optimum small signal gain value, or equivalently a SOA injection current, to realize a high and symmetric switching window. More specifically, an insufficient injection current reduces the small signal gain below values that result in a phase difference much less than the required of $\pi$. This in turn severely degrades the amplitude of the switching window, which may even not be opened, as it happens for example for 17 dB. Inversely, an over-biased SOA generates a small signal gain greater than the optimum value, which according to Fig. 5 affects drastically the SOA dynamics and can induce a large differential gain between the counter-propagating clock components. This in turn induces a strong phase modulation and makes the phase difference between the counter-propagating clock pulses exceed by far $\pi$. In this manner fluctuations occur in the switching window, which becomes dented and distorted, as for example for 29 dB. These simulation results are confirmed from the characterization of the phase dynamics of bulk SOAs [32] as well as from their exploitation in interferometric configurations for the demontration of all-optical logic applications [33]. Therefore, the SOA small signal gain and hence the injection current must be carefully selected to lie within a range of values that ensure an acceptable switching window. Provided that this condition is satisfied, the exact value that optimizes the switching window can be chosen depending on the specific shift register application. More specifically, Fig. 7 reveals that as the small signal gain increases, the width of the window is significantly reduced because this results, according to Fig. 5, to the creation of a higher differential gain. This
in turn is highly desirable for ultrafast applications. The fact that the small signal gain must increase to account for higher operating frequencies is also in accordance with experimental results obtained from SOA-based interferometric configurations. In particular, the increase of the frequency decreases the differential phase shift to values less than $\pi$, which in turn can be compensated for by increasing the SOA injection current and hence the small signal gain [34]. The price paid for this increase is that more costly, complex and power consuming current sources with the associated driving electronics are required.

Fig. 8 depicts the influence that the switching energy, $E = U_{\text{tot}}$, has on the switching window. This is the energy required to achieve a differential phase shift of $\pi$ between the counter-propagating clock pulses and hence full constructive interference at the transmission output. From a practical point of view, it must be low enough so that it can be provided from commercially available optical amplifiers. Its maximum allowable value, on the other hand, is constrained by the saturation characteristics of the SOA and the corresponding energy, which typically is 1 pJ. The observation of this figure reveals that as the energy increases, the switching window is shifted towards the right of the horizontal axis in order to achieve the highest degree of contrast ratio. This means that the temporal deviation, $t_d$, takes positive values, or equivalently the control pulse lags behind the CW pulse. This behavior is attributed to the fact that since an intense control pulse causes a deep saturation of the SOA, according to Fig. 3, it must arrive later than the CW pulse so that the latter exhibits an unsaturated SOA while the CCW pulse a recovering SOA and the required gain difference between these two clock counterparts can be created. On the contrary, if the strong control pulse arrives earlier in the SOA then both CW and CCW pulses will experience a partially recovered gain and the quality of switching will be degraded. Inversely, a control pulse of reduced energy, which cannot alter significantly the SOA properties, must arrive earlier at the SOA than the CW pulse, so that the latter experiences a higher gain than its counterpart, which is sufficient to create the necessary differential shift. In that case the values of $t_d$ are negative and the curves are shifted to the left as the energy decreases. If the control and CW pulses are appropriately synchronized so that the former arrive at the SOA before the latter, then the energy required for switching is 100 fJ, which can be also seen in Fig. 8 and is close to the experimental value [10]. At the same time, it can be observed that the switching window width increases and decreases with an increase and decrease of the control energy, respectively, which is also in accordance with other similar simulation results [35]. This can be explained by recalling that the switching window is created by the CW and CCW clock pulses that exhibit the SOA fast saturation and slow recovery characteristics, respectively. If the energy is increased thus, then the SOA becomes strongly saturated so that the CCW pulse has enough time to see a partly recovered gain. In contrast, if the energy is decreased, then the SOA initial gain is also decreased but to a value that is significantly higher than the final, saturated one, so that the time interval of the recovery region that the CCW pulse must lie within is much shorter. This behavior is similar to the one described in Fig. 6. For high line rate memory applications, an energy value below 100 fJ is thus sufficient, while for packet buffering applications it must increase over this value. This has also a physical meaning, since the information bits of a packet have less average power compared to the bits of a full duty cycle stream. Therefore, the power and hence the energy per packet bit must be increased to compensate for this difference and reach the same level required for switching. In the latter case, however, the price paid is the increase in the cost and complexity of the EDFAs, which they must be capable of providing much more optical power. Note also that if the results for the switching window size are considered in combination with the ones of Fig. 7, then the interplay between the energy and the small signal gain that was mentioned in Fig. 5 can be explained once again.

Fig. 9 shows the dependence of the switching window on the control pulse width. As this parameter is reduced, the window is shifted to the left and its size is also reduced. This behavior can be understood in combination with Fig. 4, in which, as it was mentioned, different control pulse widths result in a different gain transition region of the SOA. This in turn affects differently the CW and CCW signals and consequently the output of the shift register. More specifically, since a short control pulse of appropriate energy can quickly saturate the SOA, this essentially means that it must advance with respect to the CW pulse, otherwise the fast saturation will be accompanied by a quick gain recovery and the CCW pulse will see a highly recovered gain that is very close to that of its counterpart. As a result of the SOA fast saturation, the CCW pulse has inevitably less effective time to arrive at the SOA [18], which enables the creation of a narrow switching window. The opposite occurs if the control pulse width is increased, because in that case the SOA needs more time to be brought to saturation and the control pulse must by all means arrive after the clock pulse. If this synchronization condition is not satisfied and the control arrives earlier, then due to its long pulse width it will need more time to alter the gain dynamics of the SOA so that finally the difference between the gains (phases) of the CW and CCW pulses will be very small. Therefore, this parameter must be properly adjusted according to the specific application that the shift register must serve, and can be provided from a wide range of available laser
sources [36]. Here it must be also noted that, as it was mentioned, the control pulse width in the proposed model is over 2 ps, which justifies not taking into account the intraband non-linear gain compression effects. This in turn results in a uniform shape of the switching window in all curves, except of course when investigating the influence of the small signal gain, which is not the case, however, in other models of the SOA-assisted Sagnac switch where control pulses less than 2 ps were used. In that case, the intraband effects are more pronounced causing amplitude fluctuations of the switching window, which may even take the form of an oscillating multi-peak structure [22].

The switching window variation versus the asymmetry of the loop is shown in Fig. 10. This figure indicates that as the asymmetry increases, the curves are shifted to the right so that \( t_d \) is positive and the control pulse is delayed with respect to the CW pulse. The physical meaning of this behavior is that since under this condition the CCW pulse needs more time to arrive at the SOA, the control pulse has enough time to reach the SOA and induce the required phase difference. On the contrary, if the asymmetry decreases, the curves are shifted to the left or equivalently to negative values of \( t_d \), which in turn implies that the control must be the leading pulse so as to saturate properly the SOA before the CCW pulse arrives. At the same time, it can be observed that the size of the switching window follows the asymmetry variation. As the SOA offset is reduced thus, the switching window size decreases too, which is highly desirable for ultra-high speed applications. The opposite occurs as the asymmetry increases, which would be ideal for storing an entire packet, such as in all-optical packet switching networks [3]. Furthermore, a change of the fixed offset time, which in turn corresponds to an effective movement of the SOA position in the loop, results in a different time delay for which the maximum contrast ratio is achieved. More specifically, when the time delay is equal to \( \tau_{\text{asym}} \) or \(-\tau_{\text{asym}}\), both CW and CCW clock components experience an unsaturated or partially recovered SOA gain, respectively. In that case, the situation \( t_d = \pm \tau_{\text{asym}} \) is equivalent to a zero SOA displacement from the center of the loop so that the desired phase difference and hence optimum switching cannot be achieved. As the time delay is varied either side of \( \pm \tau_{\text{asym}} \), a phase difference begins to develop between the clock counterparts so that gradually the majority of the input power exits at the transmission port. In order to ensure thus an enhanced performance, the time delay must be less than \( \pm \tau_{\text{asym}}/2 \), which can be considered as a general rule of thumb. The plus and minus sign depends on whether a wide or a narrow switching window is desired, according to the above interpretation of Fig. 10.

The final parameter that is examined is the SOA carrier lifetime, which is depicted in Fig. 11. Clearly, the curves are shifted to left and the switching window width becomes shorter as this parameter decreases. This happens because in that case the SOA gain is quickly recovered and so the control pulse must arrive first to saturate the SOA in time and induce the necessary phase shift. This in turn results in a narrower window, in a way similar to the one described in Fig. 9 concerning the moment that the CCW pulse enters the SOA. For ultrafast applications, it is imperative thus to significantly decrease the carrier lifetime, which can be achieved by increasing the SOA bias current or using a longer SOA [25]. The first method has, however, a limited efficiency, so that other gain recovery techniques must be applied, such as the injection of a continuous wave strong holding beam [37] or the use of an assist light near the SOA transparency point [38]. Although, these techniques can speed-up the gain recovery rate, at the same time they can greatly distort the shape of the switching window so that care must be taken to prevent performance deterioration [39]. This can be achieved by ensuring that the width of the control and clock pulses as well as the loop asymmetry are small enough so as to avoid the creation of an undesirable secondary switching window. The requirement for a decreased pulse width, however, can be satisfied only by using optical sources of increased complexity. Moreover, a pulse width well below 2 ps may degenerate the performance of the shift register due to intense non-linear intraband effects that occur in that case inside the SOA. On the other hand, the second method has, as it was mentioned, a negative impact on the shape and width of the switching window. At the same time, an increase of the physical dimensions of the SOA imposes significant limit on the maximum permissible operating frequency [40]. More specifically, if the SOA transit time, which in turn is determined by its length, is greater than half the bit period, then a control pulse interacts with more than one counter-propagating clock pulses causing undesirable differential phase shift. This control pulse interaction with multiple clock pulse components leads to partial switching of unwanted bits, which in turn degrades the quality of the output pulse stream. These problems can be overcome if the completely different technological approach of quantum-dot SOAs is used [41]. These devices are characterized by the very wide gain bandwidth, the inhomogeneous broadened gain spectra, the high saturation power, the fast recovery time of the order of hundreds of fs that can enable the achievement of ultra-high switching speeds and the low pattern dependence that arises from the decoupling of gain and refractive index modulation [42]. Intense research efforts continue in this new field of optical technology so as to translate its attractive features to a comparative advantage over bulk and quantum-well amplifiers and exploit it in various all-optical signal processing tasks. Obviously, these severe technological restrictions are...
relaxed if an entire packet must be stored, since from Fig. 11 the necessary wider window can be achieved with a larger carrier lifetime.

Finally, it must be noted that another way for assessing the validity of the developed model is by comparing Figs. 7–9 and 11 with Fig. 10. More specifically, if for example a narrow switching window is desired then, according to Figs. 7–9 and 11, a high small signal gain, a low energy, a short pulse width and a small carrier lifetime are required, respectively. From the observation of the same figures it can be also deduced that these requirements are satisfied when the parameter \( t_d \) is negative or equivalently when the control pulse arrives earlier at the SOA than the co-propagating clock pulse. If a negative value of \( t_d \) is subsequently replaced in Fig. 10, it can be seen that the maximum contrast ratio is obtained for a decreased asymmetry, which in turn is necessary in order to obtain a narrow switching window. The opposite occurs obviously when a wide switching window is required. The comparison of these figures according to this rational reveals thus that there is an excellent qualitative agreement between them, which proves the robustness of the simulation analysis.

5. Conclusion

In conclusion, we have comprehensively analyzed the switching characteristics of an all-optical shift register implemented with a SOA-assisted switch in a feedback configuration. For this purpose, numerical simulations have been carried-out using a set of equations that describe the interaction between the control and clock pulses in the switch as well as the output power variation caused by changing their relative delay. The switching window created through this procedure is evaluated in terms of its contrast ratio and width, which are governed by several critical operational parameters. The required degree of performance depends on the specific shift register application, which in turn determines the selection and combination of these parameters. Since the aggregate capacity is the inverse of the temporal size of the switching window, a narrow switching window is necessary in order to meet the increasing bandwidth demand that is driven by the broadband services and the associated applications. The initial technical requirements in order to achieve this goal are a switching energy less than 100 fJ, a small signal gain over 20 dB and a carrier lifetime less than 100 ps. Although the two first requirements can be satisfied by simply using commercially available EDFAs and appropriately adjusting the SOA injection current, respectively, the third requirement essentially constitutes the major limiting factor that impedes direct extension to higher rates. A way to overcome this problem is by deploying either complex gain recovery enhancement techniques or alternatively the novel technology of quantum dot SOAs. Furthermore, since the duration of the switching window is lower-limited by the width of the control pulse, a value of less than 10 ps is sufficient at 10 GHz. For higher line rates, however, where the pulse width must be significantly reduced to less than a few ps, the non-linear intraband carrier dynamics that are present in active devices like the SOA in the Sagnac switch must be seriously taken into account since they can ultimately limit the size and shape of the switching window. This in turn affects the asymmetry value, which for a short switching window must be higher than but also close to the pulse width as well as less than half the operating period. This parameter, however, can be easily adjusted using commercially available optical delay lines and does not impose a technical restriction. On the other hand, these requirements can be relaxed when the shift register is required to function as a packet buffer, since in that case the switching window must be wider, but at the cost of inevitable energy increase. For both shift register applications, the absolute value of the time delay between the control and clock pulses must be less than half the asymmetry of the loop. Although, the main results of this work have been obtained for an operating frequency of 10 GHz, they can be also extended for higher frequencies in a similar manner. In this sense, the developed model is suitable for investigating and optimizing the operation of a variety of more complex all-optical signal-processing circuits, in which the shift register is the basic building block.

References


BOOK REVIEW


The book provides a fundamental overview of the field of photonic crystal fibres, their properties and unique features. After an introduction, Chapter 2 describes fundamentals of photonic crystal waveguides, especially the development from one- to three-dimensional photonic crystal optical waveguides. The book also addresses the issue of the design of efficient structures for the creation of photonic bandgaps and silica-air photonic crystals are introduced as a first step towards the silica-based photonic crystal fibre technology. Chapter 3 contains a description of 11 different theoretical and numerical methods applied in the analysis of photonic crystal fibres. Chapter 4, the fundamental issues of the fabrication of photonic crystal fibres are described. This include elements such as perform realisation, fibre drawing, as well as a description of microstructured fibres in new materials. Chapter 5 describes the basic issues of the presently most widely used class of photonic crystal fibres, namely the high-index-core fibres. The chapter includes a description of fundamental waveguiding properties. Chapter 6 focus on the photonic bandgap class of PCFs. The concept of air-guiding fibres will be discussed and reviewed. Finally, Chapter 7 contains descriptions of some of the most significant applications of photonic crystal fibres known at present time. Especially, the area of applications is developing at a very high speed because the photonic Crystal Fibres very often provide completely new and alternative functionalities compared to standard optical fibres. This book is not only a very god review but also a comprehensive handbook of the field of PCFs.

Robert Schreiber