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An all-optical switch of Mach–Zehnder interferometer type using an active fibre ring resonator*

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We propose an all-optical switch of the Mach–Zehnder interferometer type using an active nonlinear ring resonator and analyse the significance of the parameter A, a product of gain and total loss, for performing an ideal 1 by 2 switch. We found that in the range of $1-\kappa \leq A \leq \sqrt{1-\kappa}$, the increment of A can compensate the losses inside the ring, therefore increase the finesse of the ring and enhance the nonlinearity contribution to reduce the switching power threshold effectively. We also emphasize the importance of the initial switching point and discuss the feasibility of utilizing a high-nonlinear fibre in the ring.

Keywords: optical switching, fibre-optical devices, interferometer
PACC: 4265P, 4281W, 0760L

1. Introduction

Optical switches are of much importance for the next generation of optical communication systems, especially for access network (AN) applications. Nonlinear optical switches have a better potential due to good accordance with the main development tendency of optical communications: namely, faster operation, less requirement of energy and the compactness of devices. All-optical switching devices based on optical fibre offer great promise for reducing the complexity of the systems.

However, ordinary optical fibre possesses extremely low n_2 nonlinearity. For a typical configuration of the optical fibre switch, simply constructed by an unbalanced nonlinear Mach–Zehnder interferometer (MZI), the power threshold for switching may exceed 100 W in order to make a π rad of nonlinear phase-shift difference between the two arms. This is easily evaluated from $\lambda A_{\rm eff}/2n_2\Delta L$, where $A_{\rm eff}$ is the effective cross section of a single-mode fibre at 1.55 μm, which is about 20–200μm^2; ΔL is the path-length difference of 10m between two arms.

Heebner *et al* proposed a method to reduce the requirement of threshold switching power by 4 or more orders of magnitude to the level of milliwatts by introducing a fibre ring resonator with nonlinear contribution into one arm of an MZI.[1] Recently, they applied their theory on nonlinear ring to the optical waveguide consisting of a side-coupled integrated spaced sequence of resonators (SCISSOR) and studied the linear and nonlinear optical properties of such sequence of microresonators.[2,3]

The main advantage of their MZI-type optical switch is that the ordinary silica fibre can be used in their switch configuration with the aid of enhanced 'intrinsic' nonlinearity of silica fibre by the resonance.[1] It is necessary to point out that, in fact, the switch in their paper is not an ideal 1 by 2 switch that is vital for routing of the information. The location of the initial point (original state of the ring) must be considered (they discussed this in a later paper, but not for the switch [2,3]), which can be seen clearly from the formula: $I_{\rm io} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\varphi_{\rm eff})$, where i=1, 2 represents the two output ports, I_1, I_2 are the light intensities in the two arms just before the second 3dB coupler, respectively (as shown in Fig.1(b)), $\Delta\varphi_{\rm eff}$ is the effective phase difference between the two arms. When their switch is 'off', the resonator is ex-

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actly matched to the resonance condition, namely the frequency of weak light is just located at the centre of the resonance spectrum. But sometimes there is almost no light after the ring but before coupler, namely $I_1 \approx 0$, as will be seen from our analysis later. This means that one may obtain a signal from all output ports with the use of a 3dB coupler, although the output can be switched to one port completely by controlling $\Delta\varphi_{\text{eff}} = \pi$ and detuning the ring out of resonance when the light intensity increases to some range and the switch is 'on'.

Since 1982 the linear optical properties have been described, the power-transfer characteristics of the fibre ring resonator have found applications in interferometric sensing,[4] dispersion-compensation [5] and applications in such devices as differential amplifiers [6] and bistable optical elements [7] whose operation relies mainly on the nonlinear power-transfer characteristics of the resonators. In 1991, Okamura and Iwatsuki investigated the optical properties of an active ring (Er-doped fibre ring) neglecting the optical nonlinearity of fibre and found a finesse enhancement with the gain in the ring increasing in a certain range to compensate the round-trip optical loss.[8]

In our paper, an active ring resonator is also utilized in one arm of an MZI to compensate for the introduced loss in the ring: for instance, an additional loss will appear when connecting other components. In order to reduce the switching power more effectively we also suggest using fibre with high nonlinearity. To the best of our knowledge, the nonlinear phase-transfer characteristics of an MZI-type switch such as ours have not been previously studied.

2. Theory

The configuration of our nonlinear active MZI-type switch is shown in Fig.1. A nonlinear active fibre ring resonator is constructed by taking one output of a coupler C_0 (with an intensity loss coefficient γ and coupling coefficient κ), and connecting it to an amplification device A (with a gain G) using a section of fibre of length L with high nonlinearity (the attenuation coefficient $a = \exp(-\alpha L)$), then connecting to one input port, as shown in Fig.1(a). Such a device exhibits optical resonance when light traversing the ring acquires a phase shift of an integer multiple of 2π. In real application, we should insert a narrow band-pass filter in the ring to suppress the lasing effect at frequencies other than that of the input light due to the amplified spontaneous emission (ASE). And we should also introduce an isolator to avoid the reduction of finesse due to stimulated Brillouin back scattering (SBBS).

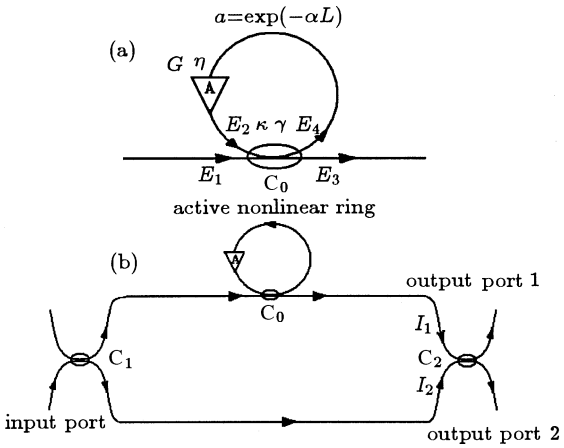


Fig.1. Configuration of an all-optical switch of Mach–Zehnder type with an active nonlinear ring resonator: (a) structure of an active ring resonator, (b) outline of a nonlinear switch of Mach–Zehnder type.

The relations between the electric fields of four ports can be derived from the set of equations the coupler C_0 obeys:

$$\frac{E_4}{E_1} = \frac{\mathrm{i}\sqrt{\kappa(1-\gamma)}}{1 - A\mathrm{e}^{\mathrm{i}\varphi}}, \tag{1}$$

$$\frac{E_3}{E_1} = \sqrt{(1-\gamma)}\mathrm{e}^{\mathrm{i}(\pi+\varphi)}\frac{(A/\sqrt{1-\kappa}) - \sqrt{1-\kappa}\mathrm{e}^{-\mathrm{i}\varphi}}{1 - A\mathrm{e}^{\mathrm{i}\varphi}}, \tag{2}$$

where φ is the phase shift of single trip of the ring. We define the parameter $A = a\sqrt{(1-\kappa)(1-\gamma)(1-\eta)G}$ as a product of gain and total loss. The intensity-magnification M is given by

$$M = \frac{I_4}{I_1} = \frac{E_4 E_4^*}{E_1 E_1^*} = \frac{\kappa(1-\gamma)}{1 + A^2 - 2A\cos\varphi}. \tag{3}$$

The finesse of the ring F is defined as a ratio of the free spectral range (FSR) and the full width at half maximum (FWHM) as

$$\text{finesse} = \frac{\text{FSR}}{\text{FWHM}} = \frac{\pi}{2a\sin\dfrac{\sqrt{A(1-A)^2}}{2A}}. \tag{4}$$

From the finesse curve versus A (Fig.2), it is easy to draw a conclusion that one can control the parameter A to get higher finesse. When the parameter A approaches unity, the finesse tends towards infinity. Unity is the limit of A because we must avoid unnecessary amplification. So, in real application, we may only use a gain in a fixed range.

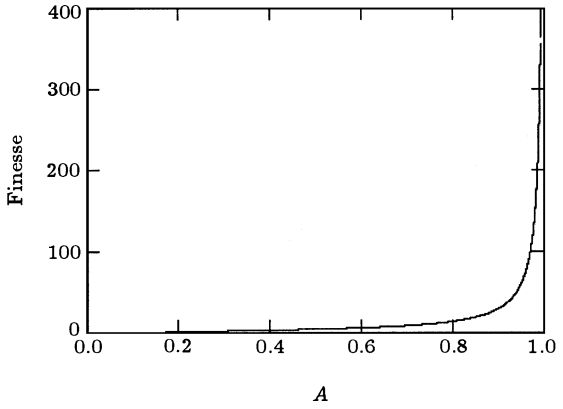


Fig.2. The finesse of a ring as a function of parameter A.

The effective phase difference between port 3 and port 1 of the coupler is expressed as

$$\varphi_{\rm eff}(\varphi,\kappa,A) = \pi + \varphi + \arg[(A/\sqrt{1-\kappa}) - \sqrt{1-\kappa}{\rm e}^{-{\rm i}\varphi})] - \arg(1 - A{\rm e}^{{\rm i}\varphi}). \quad (5)$$

The curve of $\varphi_{\rm eff}(\varphi,\kappa,A)$ versus φ has stair-shape with a series of 2π phase transition areas, which appear near resonance of the ring, as shown in Fig.3. The plot below demonstrates these curves without gain (G=1) (where η=0.1, γ=0.01, and a=0.98).

The parameter A is vital for the switch since the shape of the curves, or more exactly, the slope and width of 2π phase transition area near the resonance, can be strongly affected by A. When A approaches to but is less than unity (with the parameters η, γ, a fixed), the stairs become steepened. The closer A is to unity and κ to zero, the narrower the transition area, and the sharper the edges of transition area.

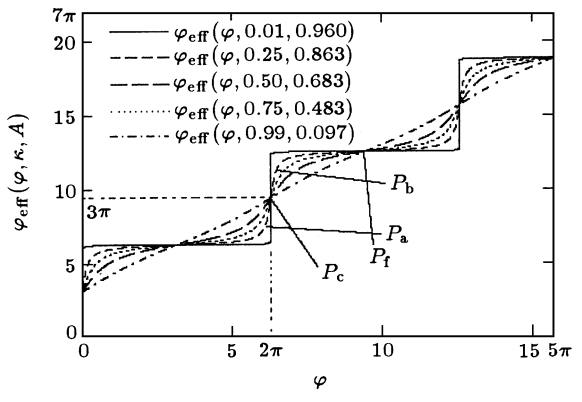


Fig.3. Effective phase difference between port 3 and port 1$\varphi_{\rm eff}$ as a function of phase of single trip φ with fixed parameters κ, A.

One can make use of the transition areas to get a π phase shift from the centre of the area (the $P_{\rm c}$ point, just at resonance) to a certain point (in fact, only the far point $P_{\rm f}$ is suitable for this) proposed by Heebner *et al*, utilizing the resonance-enhanced optical nonlinearity in the silica fibre ring. It is true that for the ring at resonance the intensity inside would be much higher than that of out-of-resonance; the increasing contribution of optical nonlinearity to the phase results in a detuning of the ring from the resonance point. In the ordinary case, however, to get a π phase shift, the ring has to experience a wider phase change than that between points $P_{\rm a}$ and $P_{\rm b}$ suggested by us. When the ring is out of resonance, light inside is relatively weak, and it is difficult to get a bigger nonlinear contribution to keep on driving the ring to the far point. This means more energy or power may be wasted here to perform a switching.

One may reduce the switching threshold more efficiently using our two points, located near the resonance point (see Fig.3). The important thing to be emphasized is that the spacing of $P_{\rm a}$ and $P_{\rm b}$ will be shortened with the parameter A approaching adequately close to unity.

Considering the symmetry, one may express the phases of $P_{\rm a}$ and $P_{\rm b}$ as $\varphi_{\rm a,b} = \varphi_{\rm c} \mp \varphi_0$, where $\varphi_{\rm c} = 2m\pi$ (m=1, 2, 3, ...). We have the phase difference between $P_{\rm a}$ and $P_{\rm b}$ in the output after the ring

$$\begin{aligned}&\Delta\varphi_{\rm eff}(\varphi_0,\kappa,A)\\ =&\varphi_{\rm eff}(\varphi_{\rm b}) - \varphi_{\rm eff}(\varphi_{\rm a})\\ =&2\varphi_0 + \arg[(A/\sqrt{1-\kappa}) - \sqrt{1-\kappa}{\rm e}^{-{\rm i}\varphi_0}]\\ &- \arg(1 - A{\rm e}^{{\rm i}\varphi_0})\\ &- \arg[(A/\sqrt{1-\kappa}) - \sqrt{1-\kappa}{\rm e}^{{\rm i}\varphi_0}]\\ &+ \arg(1 - A{\rm e}^{-{\rm i}\varphi_0}). \end{aligned} \quad (6)$$

In order to obtain a π phase shift from $P_{\rm a}$ to $P_{\rm b}$, we must have a condition $\Delta\varphi_{\rm eff} = \varphi_{\rm eff}(\varphi_{\rm b}) - \varphi_{\rm eff}(\varphi_{\rm a}) \geq \pi$, and we find that $A \geq 1 - \kappa$.

Figure 4 shows the curves of $\Delta\varphi_{\rm eff}(\varphi_0,\kappa,A)$ as functions of φ_0 in the case of no gain with fixed parameters η=0.1, γ=0.01 and a=0.98 and chosen parameter κ. The curve $\Delta\varphi_{\rm eff}(\varphi_0, 0.146, 0.855) \sim \varphi_0$ approaches a critical case when $A \sim 1 - \kappa$. It is obvious that the smaller the parameter κ is, the more easily one obtains π phase shift from $P_{\rm a}$ to $P_{\rm b}$ by using smaller $|\varphi_0|$. This means a detuning (or power) smaller than usual is required for switching. Notice that with an adequate increment of A all curves incline to the left to help reduce the value of φ_0 required for switching threshold.

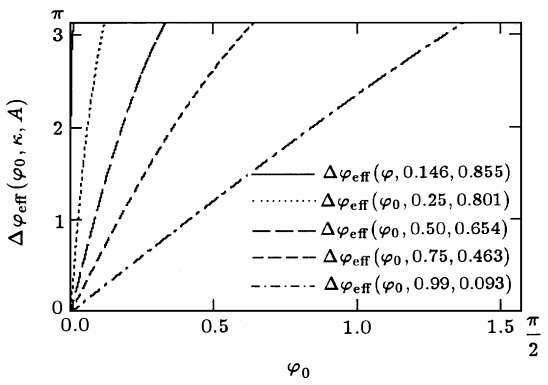


Fig.4. Phase difference $\Delta\varphi_{\rm eff}$ between points $P_{\rm a}$ and $P_{\rm b}$ as a function of the offset from the resonance φ_0 with fixed parameters κ, A.

The transmission minimum of the ring at resonance is

$$T_{\rm m} = T_{\rm m}(A,\kappa) = (1-\gamma)\frac{A^2/(1-\kappa)+(1-\kappa)-2A}{1+A^2-2A}. \quad (7)$$

To avoid unnecessary amplification of the signal after the ring, $T_{\rm m}$ must be less than $1-\gamma$; we can find that $A \le \sqrt{1-\kappa}$. Fixing the parameter γ (e.g. let us consider the lossless case for the coupler C_0, namely γ=0), and choosing some typical values of parameter κ, we plot the $T_{\rm m}$ as a function of parameter A, as shown in Fig.5. It is clear from the curves that, if the ring without gain (G=1) is originally located at a certain point for one of the curves, one can fill up the pits in the transmission curves (to let $T_{\rm m} \to 1-\gamma$) through a small increment of A (or more exactly, of G). In real application, G is limited in a small range to guarantee the condition $1-\kappa \le A \le \sqrt{1-\kappa}$.

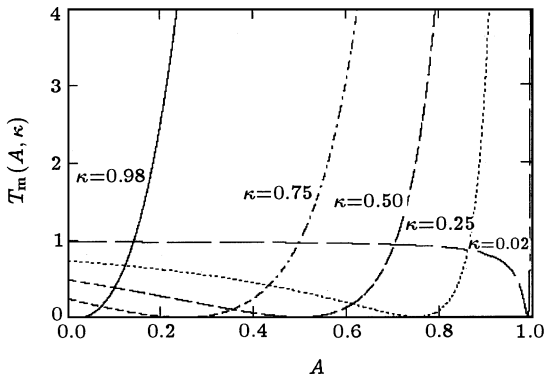


Fig.5. Transmission minimum $T_{\rm m}$ as a function of the parameter A with fixed κ.

Figure 6 shows a typical change of transmission minimum under various values of A with the other parameters fixed as κ=0.3, γ=0.01. It is easy to see the phenomenon of filling up when the parameter A approaches $\sqrt{1-\kappa} = 0.8366$. In fact, this is not a bad thing for performing 1 by 2 switching, since one can guarantee that both the output and input of the ring will be almost the same for any pair of points that may bring π phase shift, like the intensity in another arm of the MZI if all couplers are of 3dB.

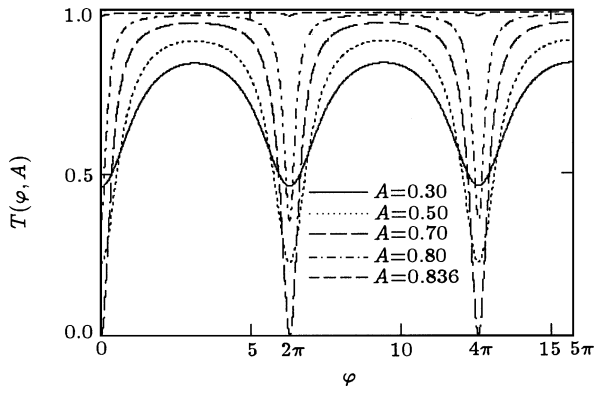


Fig.6. The phenomenon of filling up: transmission of the ring T as a function of the phase of single trip φ with fixed parameter A.

3. Nonlinear switching

Here we consider a fibre constructing the ring with Kerr nonlinearity. The optical nonlinearity can make a contribution to the phase shift of a single trip, since the phase shift is the accumulation of small contributions $d\varphi$:

$$\varphi = \int_0^L d\varphi = \varphi_{\rm L}+\varphi_{\rm NL} = 2m\pi-\varphi_0+\frac{2\pi a n_2 P_4 L}{\lambda A_{\rm eff}}, \quad (8)$$

where $\varphi_{\rm L}$, $\varphi_{\rm NL}$ represent the linear and nonlinear phase, respectively. n_2 is the coefficient of Kerr nonlinearity, which is about $2.6\times10^{-20}{\rm m}^2/{\rm W}$ for ordinary silica fibre. P_4 is the light power inside the ring. φ_0 describes an initial offset from the resonance at point $P_{\rm a}$. The phase difference between $P_{\rm a}$ and $P_{\rm b}$ can be written as

$$\begin{aligned}\Delta\varphi_{\rm eff} &= \Delta\varphi_{\rm eff}(P_{1{\rm a}},P_{1{\rm b}},\varphi_0)\\ &= \int_{P_{1{\rm a}}}^{P_{1{\rm b}}} \frac{d\varphi_{\rm eff}}{d\varphi}\frac{d\varphi}{dP_4}\frac{dP_4}{dP_1}dP_1, \end{aligned} \quad (9)$$

where $P_{1{\rm a}}$ and $P_{1{\rm b}}$ denote the powers in the arm before the ring at the points $P_{\rm a}$ and $P_{\rm b}$. Usually, we may reasonably define $P_{1{\rm a}}$=0. Fixing λ=1.55μm, a =0.98, L=10m, n_2=$2.6\times10^{-17}{\rm m}^2/{\rm W}$, taking $A_{\rm eff}$=20$\mu{\rm m}^2$ and completing the integral, we get curves of $\Delta\varphi_{\rm eff}(P_{1{\rm b}},\varphi_0)$ as functions of $P_{1{\rm b}}$ and the parameter φ_0 (see Fig.7).

From the curves we find that the closer to a certain point at the left near the resonance point $P_{\rm a}$ is

($\varphi_0 = \pi/16$ is best curve in our case), the more easily we get a π phase shift using smaller power (or intensity). Notice that $\varphi_0 = 0$, corresponding to the Heebner point, is the critical case to get a π phase shift, for the line $\Delta\varphi_{\rm eff}(P_{\rm 1b}, \varphi_0) = \pi$ is its asymptote. It is almost not expectable to get a π phase shift in the case of $\varphi_0 < 0$ for the power range less than 100mW, because there is no intersection with the asymptote (e.g. for $\varphi_0 = -\pi/64$). From the integral process we find that when the parameter A increases properly, the curves ($\varphi_0 > 0$) may change in the direction to intercept a smaller power required for switching with the line $\Delta\varphi_{\rm eff}(P_{\rm 1b}, \varphi_0) = \pi$. This means that A can help to reduce the power threshold for our MZI-type switch.

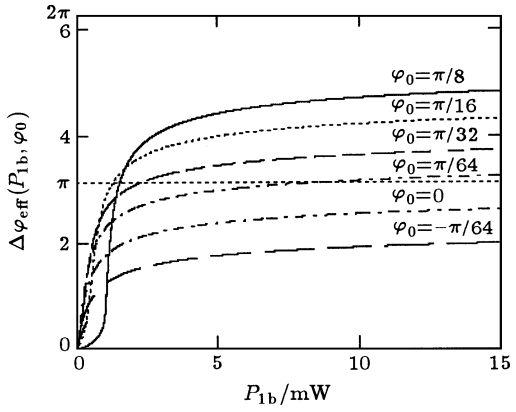


Fig.7. Effective phase difference $\Delta\varphi_{\rm eff}$ as a function of the power before the ring $P_{\rm 1b}$ and the parameter φ_0.

4. Discussion

It is almost impossible to use fibre with low attenuation but low nonlinearity such as single mode silica-based fibre for constructing the MZI-type switch because of the difficulty in manufacturing a coupler with small coupling coefficient ($\kappa \ll 0.02$) and loss ($\gamma \ll 0.02$) and in controlling the total loss in the ring. From our analysis we find that, it does not matter if the losses in the coupler and ring are not relatively low, as we can use an amplification unit to compensate: for example, a semiconductor optical amplifier (SOA), which has short scale. Moreover, an adequate gain can help to obtain better finesse and enhance the nonlinearity contribution inside the ring, and therefore reduce the power threshold for switching.

Another parallel way to reduce the power threshold is directly using fibre with higher nonlinearity in the ring, such as chalcogenide glass fibre, the nonlinearity of which is 2–3 orders of magnitude greater than that of ordinary silica fibres but with relatively small losses (e.g. n_2 of As_{40} S_{50} Se_{10} is about 400 times larger than that of ordinary silica fibres).[9] This may also reduce the power requirement in the ring. We may use a coupler with relatively large coupling coefficient, even the 3dB coupler that is available from the usual technique.

Combining the advantages of using adequate gain, high-nonlinear fibre and the two points proposed by us in the transition area, we may easily get a power threshold lower than milliwatts, even down to the submilliwatt range (see Fig.7). In fact, an ideal all-optical 1×2 switch is achieved, i.e. when the signal is very weak, it can be only obtained from one output port, while with increase of the signal power to some range, the signal goes to another output port completely.

We may improve our switch using a nonlinear coupler in our configuration, namely the coupling coefficient κ becomes controllable by the light intensity.[10] Maybe, this will help to reduce the requirements for the ring fibre, such as the length and nonlinearity. Since the shorter the ring is, the faster the switch is, we should let κ change towards smaller values.

A rough calculation from cavity lifetime FLn/c shows that the switching time of a ring shorter than 0.1 metre with finesse $F \sim 10$ (e.g. produced by the waveguide technique) can easily reach to tens of nanoseconds, which is better than that of some switches available commercially, but with the switching power still in the mW range.

There are some modern waveguide methods that can be used to manufacture an all-optical switch as proposed by us, in fact. A nonlinear ring with diameter in micrometre range (see Ref.[2]) coupled with a SOA area can be easily fabricated on the waveguide substrate. With the aid of a quite mature waveguide technique, an integrated all-optical switch of MZI type with three couplers and a ring can be made. This switch has some obvious advantages, such as compactness, integratability, and higher response speed (because of the shorter scale of ring resonator).

5. Conclusion

In conclusion, the parameter A as a product of gain and total loss is very important, since in the range of $1 - \kappa \leq A \leq \sqrt{1-\kappa}$, as we analysed, the increment of A can help to compensate the losses inside the ring, and therefore increase the finesse of the ring and enhance the nonlinearity contribution, which

is very useful for reducing the switching power threshold more effectively. Another important thing is the initial switching point of the ring. By adequately constructing the ring, including carefully choosing the fibre type with high nonlinearity and the coupler, and by controlling the gain in the ring (the A), an ideal 1 by 2 all-optical switch of the MZI type with lower threshold by using an active nonlinear ring resonator is possible.

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