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RING RESONATOR COUPLED M-Z ALL-OPTICAL SWITCH BY USING A PUMPED NONLINEAR DIRECTIONAL COUPLER*

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Abstract – We propose a new ring resonator side-coupled M-Z interferometer all-optical switch through the pumped nonlinear directional coupler. By controlling pump power P to lead the coupler reflectivity r approaching to 1, the resonator finesse will be enhanced dramatically, and then the minimum switching power in silica-based practice devices can be obtained. As a sample, we use a nonlinear coupler made by two erbium-doped fibers, and launch a 514.5*nm*-pump light into one of the cores to make the reflective- index difference between two cores. Based on the asymmetric-coupler theory, we simulate the relationship between r and P, and show that the required pump power is only 0.8mW for $r \to 1$.

Keywords – All optical switches, Mach-Zehnder interferometer, switching power, ring resonator, directional coupler, Erbium-doped fiber, nonlinear refractive index

1. INTRODUCTION

All-optical data transmissions in fiber optical communication have been realized by DWDM and EDFA technologies. However, the switching between optical channels in DWDM networks still perform electrically by using opto-electronic, opto-magnetic or mechanical-electronic devices becoming a bottleneck for future all-optical communication. Obviously, the development of all-optical switches (AOS) based on nonlinearity is important, however AOSs using ordinary fiber or silica based integrated techniques need high switching power because of the low nonlinear refractive index n_2 of silica materials.

Heebner et al. [1], proposed a new AOS in which a ring resonator (RR) is coupled with one arm of a Mach-Zehnder (M-Z) interferometer. The RR accumulates the power-dependent nonlinear phase to get an π-phase shift required by optical switching. The switching power, therefore, is reduced by four orders to be milliwatts. In their switching device, the coupler reflectivity is very large $(r \to 1)$, and the loss in RR, which can be defined as: $a^2 = (1-\gamma)e^{-\alpha l}$, is neglected.(here, γ is the insertion loss of the direction coupler, and α is the absorption per unit length, which for ordinary silica fiber is around $7\times10^{-5} m^{-1}$, and l is the length of the ring resonator). Therefore, in a lossless and short length of the RR we can consider that $\gamma \approx 0$ and $e^{-\alpha l} \approx 1$, and as a result in the lossless RR we can suggest that $a \to 1$, so that the nonlinear response is quadratically enhanced by the resonator finesse, which depends on the coupler reflectivity r only. In their configuration, the switching power is around $10mW$ for $10m$ long ring resonator, which means that the switching power-length product, an

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important characteristic of the switch device, is about $10^{-1} m.W$ (during recent years switch architecture has tried to decrease this parameter as low as possible).

Actually, in practice it is difficult to satisfy the above two conditions that $a \to 1$ and $r \to 1$. In order to compensate losses to satisfy the first condition $a \to 1$, we proposed an improved device [2], in which an optical amplifier SOA is inserted into the ring. In this paper, we suggest using a pumped nonlinear directional coupler (PNLDC) instead of the ordinary directional coupler and launching a pump light into PNLDC to control the coupler reflectivity and satisfy the second condition $r \to 1$, so that the minimum switching power can be obtained and the corresponding switching power-length product decreased to $10^{-2} m.W$, which is two times lower than before.

2. WORKING PRINCIPLE OF THE DEVICE

Figure1 shows a new designed M-Z interferometer optical switch with an RR coupled by a PNLDC. The signal light enters in port A through PNLDC and RR, and then exits from ports C or D. As we know, wavelength division multiplexing (WDM) devices are well known and useful in new communication systems that combine (couple) and separate (split) signals at different frequencies. In our case, WDM1 and WDM2 are simple couplers which are fabricated in such a way that WDM1combine signal wavelength and pump wavelength, then both signal and pump wavelength pass through the PNLDC. Because the two wavelengths are different, when the signal light resonates in the ring, the pump light should be out of the resonance; it passes through the coupler and then goes out from WDM2, which can split signal and pump wavelength from each other. The pump wavelength goes out and signal wavelength can be directed to one of the output ports, either C or D. The role of pump wavelength is that while passing through PNLDC, the refractive index of the lower arm of the PNLDC is changed and made into an asymmetric coupler.(because the lower arm and upper arm of PNLDC have different refractive indexes) which will be discussed in the next sections more clearly.

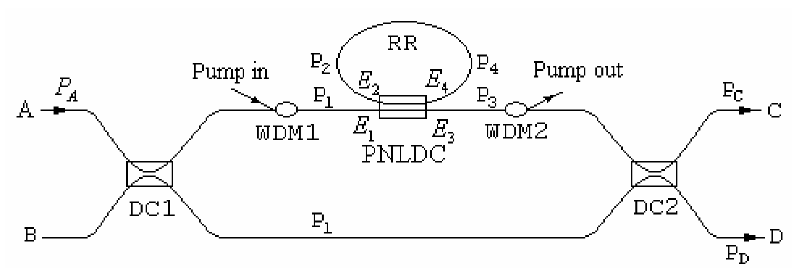

Fig.1. M-Z interferometer optical switch with a ring resonator coupled by a PNLDC

Now, we start to derive the relation between electric fields at input ports of the PNLDC (E_1 and E_2), and output ports of the PNLDC (E_3 and E_4) for signal wavelength under two basic conditions; firstly RR is lossless ($a \to 1$), and secondly the coupler reflectivity is large($r \to 1$). Signal power is weak, so the nonlinearity in the coupler medium for the signal can be neglected. The following field transfer equations are valid:

$$E_3 = rE_1 + itE_2 , \tag{1}$$

$$E_4 = itE_1 + rE_2 , \tag{2}$$

$$E_2 = E_4 \exp(i\varphi) , \tag{3}$$

where $r=(1-c)^{1/2}$ is the coupler reflectivity, $t=(c)^{1/2}$ is the coupler transmittance, c is the coupler ratio, and $r^2+t^2=1$. φ is the single-pass phase shift in the ring, which includes linear and nonlinear in two parts.

From (1)-(3), we can find the ring magnification

$$M=\frac{P_2}{P_1}=\frac{|E_2|^2}{|E_1|^2}=\frac{1-r^2}{1-2r\cos\varphi+r^2}. \tag{4}$$

In the resonant case, $\varphi=2m\pi$ ($m=0,1,2,\cdots$), (4) becomes $M_{\max}=(1+r)/(1-r)$.

At resonance, the resonator finesse can be obtained from (4)

$$F=\frac{2\pi}{\delta\varphi}\approx\frac{\pi}{1-r}\approx\frac{\pi}{2}\cdot\frac{1+r}{1-r}=\frac{\pi}{2}M_{\max}. \tag{5}$$

Therefore, the resonator finesse depends on r only.

In the M-Z interferometer consisting of two 3-dB couplers, the phase difference between two arms is equal to the phase difference between ϕ_3 at point 3 and ϕ_1 at point 1, which can be written as [2]

$$\phi=\phi_3-\phi_1=\arg\left(\frac{r-\exp(i\varphi)}{1-r\exp(i\varphi)}\right). \tag{6}$$

the nonlinear response of switching devices can be evaluated by the derivative of phase shift ϕ, with respect to input power P_1 as follows [1]:

$$\frac{d\phi}{dP_1}=\frac{d\phi}{d\varphi}\frac{d\varphi}{dP_2}\frac{dP_2}{dP_1}\approx\frac{8ln_{R2}}{\pi\lambda S}F^2. \tag{7}$$

where n_{R2} is the nonlinear refractive index, l and S is the length and the effective cross section for the ring fiber. According to (7), the increment of input power ΔP_1 will induce the increment of phase shift $\Delta\phi$, let $\Delta\phi=\pi$, we get:

$$\Delta p_1=\left(\frac{\pi^2\lambda S}{8l\,\mathrm{n}_{R2}}\right)\frac{1}{F^2}. \tag{8}$$

The increment of input power for switching is inverse proportional to the square of the finesse.

From (5), when $r\to 1$, the finesse becomes very large, and from (8), the increment of input power for switching is reduced dramatically.

Figure 2 shows the transmission at port D of the switch as a function of input signal power for different r in the data: $l=1m$, $S=50\times10^{-12}m^2$ and $n_{R2}=3\times10^{-20}m^2/W$. It is obvious that the switching power threshold can be decreased dramatically by approaching r to 1.

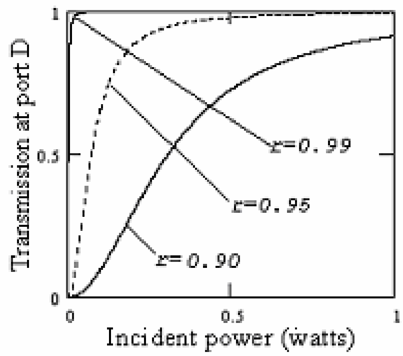

Fig. 2. Curve of output transmission at port *D* as a function of incident power for different *r*

3. CHANGING THE COUPLER REFLECTIVITY THROUGH PNLDC

However, making a coupler with coupler reflectivity $r \to 1$ is difficult in practice. We suggest utilizing a nonlinear coupler consisting of two symmetric nonlinear fiber cores doped by rare-earth ions, for example, Er^{3+}-doped fiber. For the weak signal power, the nonlinear coupler is linear. The coupler reflectivity r can be controlled by the pump power, which is incident into the lower fiber core as shown in Fig. 1.

We consider that the change of nonlinear refractive index in the lower Er^{3+}-doped fiber core depends on the pump power at wavelength 514.5*nm*. The refractive-index change Δn as a function of the pump power P can be written as [3]

$$\Delta n = \frac{n_E - n_G}{1 + (P_S / P)}, \tag{9}$$

where P_S is the saturation pump power; n_E and n_G are the refractive indexes when all erbium atoms are in the excited state and the ground state, respectively. The refractive-index difference between two cores is equal to the change of refractive index in the lower core induced by the pump power.

The pumping makes the mismatch of refractive indexes in two cores, causing the coupler to become asymmetric. If radiuses of two cores are the same, the propagation-constant difference between the two modes in the asymmetric coupler can be written as [4]

$$\Delta\beta \approx \frac{1.14(1.14V - 1)(\Delta n)}{\rho(2\delta)^{1/2} . n} \tag{10}$$

where V is the fiber-well-defined parameter in the range of $1.5 \le V \le 2.5$; ρ is the radius of the core; δ is the fractional index change at the core-cladding interface, $\delta = (n_{co} - n_{cl}) / n_{co}$; n_{co} and n_{cl} are the refractive indexes of the core and the cladding, respectively.

In the asymmetric coupler, transferring the signal power from input point 1 to output points 3 and 4 can be described as [4]

$$r^2 = 1 - \psi^2 \sin^2(\kappa z / \psi), \tag{11}$$

$$t^2 = \psi^2 \sin^2(\kappa z / \psi), \tag{12}$$

where κ is the coupling coefficient, which depends on fiber cores and their separation. In particular, the coupling coefficient drops rapidly as the separation between the two fibers increases.

The important parameter is the product of the coupling coefficient and the length of the coupling region ($\kappa.L$) during manufacturing, and by diffusing the two fibers to each other, $\kappa.L$ is controlled in real time.

ψ is the symmetry degree of coupler, which is defined as [4]

$$\psi = 1/[1+(\Delta\beta^2/4\kappa^2)]^{1/2} \,. \tag{13}$$

For the symmetric coupler, $\psi = 1$; and for the asymmetric coupler, $\psi < 1$. It is evident that in the symmetric case, (11) and (12) become the well-known relations: $r^2 = \cos^2 kz$ and $t^2 = \sin^2 kz$.

According to Eqs (10) and (13), Fig. 3 shows the curve of the coupler reflectivity *r* as a function of the symmetry degree ψ for an asymmetric coupler, which is initially a 3-dB coupler ($\kappa L = 3\pi/4$). We can see that by deviating the coupler from symmetric state $\psi = 1$ to asymmetric state $\psi \approx 0.7$, the r can be changed from 0.7 to 1.

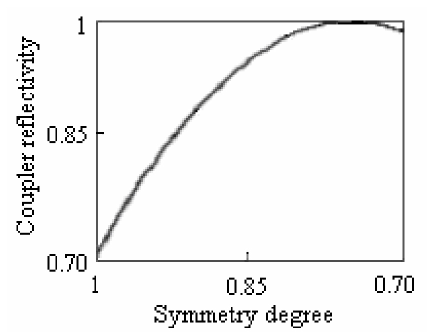

Fig. 3. Curve of coupler reflectivity *r* as a function of symmetry degree ψ for $\kappa L = 3\pi/4$

By substituting the refractive index change of the lower arm of the PNLDC (Δn) due to pumping, from Eq. (9) to Eq. (10), we can find the propagation-constant difference between two modes ($\Delta\beta$) as a function of pumping power, and finally, according to Eq (13) and (11), the coupler reflectivity can be obtained as a function of pumping power. We consider that the 1.55 μm-signal light is sent into the nonlinear coupler made by two erbium-doped fibers, and launch a 514.5*nm*-pump light into the lower core of the coupler to change its coupler reflectivity. Using the following typical data [3], [4]: *V*=2.4, $\rho \approx 1.8\mu m$, $\delta = 0.003$, $\kappa = 1cm^{-1}$, $|n_E - n_G| = 3.7\times10^{-7}$, $P_S = 1mW$ and $n = 1.46$, and taking the coupling length of coupler as $z = 3\pi/4\kappa$ for the signal, we get the curve of r as a function of the P as shown in Fig. 4. We can see that when the pump power increases from 0 to 0.8mW, the coupler reflectivity can be changed from 0.7 to 1.

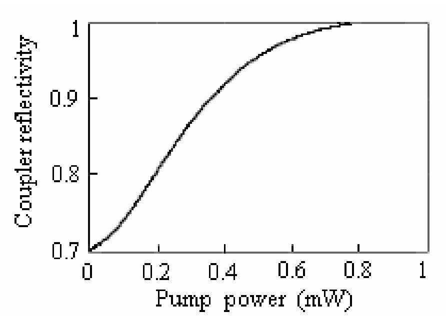

Fig. 4. Curve of the coupler reflectivity r as a function of the pump power P

4. SWITCHING RESPONSE TIME

As we know, there is a tradeoff between the switching power and the response time for optical switches. In our configuration, the switching time of device τ is limited by the RR decay time τ_c, the response time of signal fiber nonlinearity τ_f, and the response time of the nonlinear core in NLDC τ_{co}:

$$\tau = \tau_c + \tau_f + \tau_{co} . \tag{14}$$

$\tau_c \approx nlF / c$, in which nl / c is the single-pass time in the ring, and F is the finesse of the ring. By using a micro ring with a length of $0.01m$, and taking $F = 100$ and $n = 1.5$, we get $\tau_c \approx 5ns$. τ_f comes from the response time of the Kerr effect in the ring fiber, which is in order of ns. τ_{co} depends on the response time of the rare earth-doped nonlinear fiber core in the coupler at the pump wavelength. For an Erbium-doped fiber, the nonlinear refractive index n_2 is about $3\times10^{-15} m^2 / W$, which is larger than that of other nonlinear rare earth-doped fibers. However, the response speed of this fiber is very slow, about 10ms [5]. The nonlinear fiber with the fastest response time is a Samarium-doped fiber pumped by $1.06\mu m$ -light, with response time $< 5ns$, but its n_2 is only $3\times10^{-19} m^2 / W$, so that the required pump power by a YAG laser could be higher than that of an Erbium-doped fiber in 4 orders. As a tradeoff selection, we can use a Ytterbium-doped fiber with $n_2 = 0.62\times10^{-15} m^2 / W$ and $\tau_{co} = 750\mu s$, which is pumped by $1.31\mu m$ -light.

5. CONCLUSION

In conclusion, according to the best of our knowledge, for the first time, the switching device we proposed in this paper is a new kind of all-optical switch. Coupling the ring resonator to the M-Z interferometer is through a pumped nonlinear directional coupler, which is made by two rare earth-doped fibers. A pump light leads its coupler reflectivity approaching to 1, so that the resonator finesse can be greatly enhanced, and then the lowest switching power threshold in the silica-based practice devices can be obtained.

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