Enhanced all-optical switching by use of a nonlinear fiber ring resonator

John E. Heebner and Robert W. Boyd

Institute of Optics, University of Rochester, Rochester, New York 14627

Received December 14, 1998

We predict dramatically reduced switching thresholds for nonlinear optical devices incorporating fiber ring resonators. The circulating power in such a resonator is much larger than the incident power; also, the phase of the transmitted light varies rapidly with the single-pass phase shift. The combined action of these effects leads to a finesse-squared reduction in the switching threshold, allowing for photonic switching devices that operate at milliwatt power levels in ordinary optical fibers.

OCIS codes: 190.4370, 060.4370, 190.0190, 230.4320, 200.4660, 230.5750.

All-optical switching devices based on ordinary optical fiber offer great promise for reducing the complexity of optical communication systems. However, ordinary optical fiber possesses an extremely low n_2 nonlinearity. In a prototypical configuration for optical fiber switching, an unbalanced nonlinear Mach–Zehnder interferometer switches when the nonlinear phase-shift difference between the two paths equals π rad. Such a system possesses a threshold switching power given by $\lambda A_{\text{eff}}/2n_2\Delta L$.[1] For typical single-mode fiber parameters at 1.55 μm and a path-length difference ΔL of 10 m, the threshold switching power exceeds 100 W. Despite a weak nonlinearity, ordinary silica fiber has the distinction of possessing the highest nonlinearity-to-attenuation ratio of any material system. Thus, it is advantageous to design devices that make use of this property in an effective manner. It is shown below that the introduction of a nonlinear ring resonator into one of the arms of a Mach–Zehnder interferometer will effectively enhance the accumulated nonlinear phase shift and reduce the switching threshold by 4 or more orders of magnitude to the level of milliwatts. Such large enhancement requires resonant operation, which inherently demands extremely low-loss transmission characteristics found only in silica fiber.

A single-coupler fiber ring resonator is constructed by taking one output of a directional coupler and connecting it to one input port through a length of optical fiber, 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 1982 the linear optical properties of such a device were described,[2] and since then the power-transfer characteristics have found application primarily in interferometric sensing,[2] and the phase-transfer characteristics of such devices have been applied to dispersion compensation.[3] Also, many applications have been demonstrated that use nonlinear ring resonators as differential amplifiers[4] and bistable optical elements[5] in which the device operation relies primarily on the nonlinear power-transfer characteristics of the resonators. To the best of our knowledge the nonlinear phase-transfer characteristics of the device have not been previously studied.

Figure 1(a) shows the configuration of the fiber ring resonator. The directional coupler obeys the field transfer characteristics

$$E_3 = rE_1 + itE_2\,, \tag{1a}$$
$$E_4 = itE_1 + rE_2\,. \tag{1b}$$

The output from port 4 is fed back into input port 2 via an optical fiber of length L so that

$$E_2 = \exp\left(-\frac{\alpha}{2}L\right)\exp(i\beta L)E_4 \equiv a\exp(i\phi)E_4\,. \tag{2}$$

We solve Eqs. (1b) and (2) to obtain

$$\frac{E_2}{E_1} = \frac{ita\exp(+i\phi)}{1 - ra\exp(+i\phi)}\,. \tag{3}$$

The intensity-magnification factor M, the ratio of circulating intensity to incident intensity, is given by the squared modulus of this result,

$$M = \frac{I_2}{I_1} = \frac{(1-r^2)a^2}{1 - 2ra\cos(\phi) + r^2a^2} \xrightarrow[\phi=0,\,a=1]{} \frac{1+r}{1-r}\,, \tag{4}$$

where the last form of this result refers to the situation in which the incident light is resonant with the ring

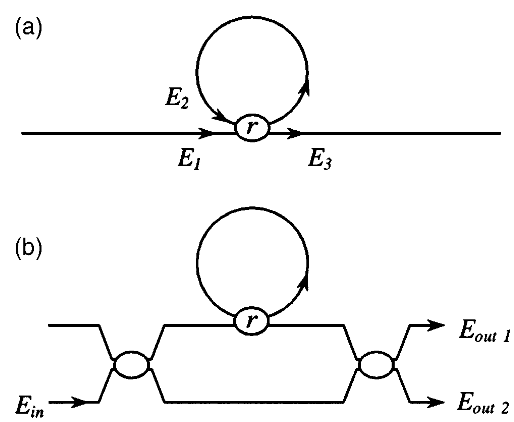

Fig. 1. (a) Nonlinear fiber ring resonator. The circulating power exceeds the incident power by the factor $(1+r)/(1-r)$, which is very large for r close to unity. (b) Switching threshold of a nonlinear Mach–Zehnder interferometer can be dramatically reduced by introduction of a nonlinear fiber ring resonator into one arm of the interferometer.

0146-9592/99/120847-03$15.00/0

($\phi = m2\pi$) and attenuation is negligible ($a = 1$). A passive ring resonator under these conditions attains the maximum ratio of circulating power to incident power that can be achieved, given by $(1 + r)/(1 - r)$. As a result of this magnification the incident power required for a desired single-pass nonlinear phase shift is reduced accordingly.

An examination of the phase-transfer characteristics of the resonator reveals an additional enhancement. We solve Eqs. (1a) and (3) for the ratio E_3/E_1 to obtain

$$\frac{E_3}{E_1} = \exp[+i(\pi + \phi)]\frac{a - r\exp(-i\phi)}{1 - ra\exp(+i\phi)}\,. \tag{5}$$

The intensity-transmission factor is given by the squared modulus of this quantity and was previously studied extensively.[2] For negligible attenuation ($a = 1$) the intensity transmission is equal to unity for all values of ϕ. The phase of the field transmission factor has not, however, been extensively studied in the context of nonlinear phase-shift enhancement. We define the effective phase shift for the resonator as the phase argument of the field transmission factor, which is the phase shift acquired by light in crossing the coupler from port 1 to port 3. For negligible attenuation the effective phase shift is given by

$$\phi_{\text{eff}} \xrightarrow[a=1]{} \pi + \phi + 2\arctan\frac{r\sin(\phi)}{1 - r\cos(\phi)}\,. \tag{6}$$

A plot of the effective phase shift versus the single-pass phase shift ϕ for different values of r is shown in Fig. 2. Near resonance ($\phi \approx 0$) the slope of the curve becomes very steep, and thus the device output phase is sensitively dependent on changes in the single-pass phase shift. A measure of this phase sensitivity is obtained by differentiation of the effective phase shift with respect to the single-pass phase shift to obtain

$$\frac{\mathrm{d}\phi_{\text{eff}}}{\mathrm{d}\phi} = \frac{(1 - r^2)a^2}{1 - 2ra\cos(\phi) + r^2a^2} \xrightarrow[\phi=0,\,a=1]{} \frac{1 + r}{1 - r}\,, \tag{7}$$

where the last form of this result refers to the situation in which the incident light is resonant ($\phi = m2\pi$) and attenuation is negligible ($a = 1$). Under these conditions, the level of phase sensitivity is exactly equal to the level of intensity magnification. The increased phase sensitivity is a purely linear effect, whereas the intensity-magnifying properties lead to additional enhancement for a nonlinear fiber. If the ring is allowed to possess a third-order nonlinearity manifested as an intensity-dependent refractive index, then the single-pass phase shift can be written as $\phi = \phi_0 + 2\pi L n_2 P_2/\lambda A_{\text{eff}}$, where ϕ_0 is a linear phase offset. The derivative of the effective phase shift with respect to input power gives a measure of the power-dependent nonlinear accumulated phase. This derivative can be expressed as

$$\frac{\mathrm{d}\phi_{\text{eff}}}{\mathrm{d}P_1} = \frac{\mathrm{d}\phi_{\text{eff}}}{\mathrm{d}\phi}\frac{\mathrm{d}\phi}{\mathrm{d}P_2}\frac{\mathrm{d}P_2}{\mathrm{d}P_1} \xrightarrow[\phi=0,\,a=1]{} \frac{2\pi L n_2}{\lambda A_{\text{eff}}}\left(\frac{1 + r}{1 - r}\right)^2$$

$$\approx \frac{8 L n_2}{\pi \lambda A_{\text{eff}}}\mathcal{F}^2, \tag{8}$$

where $\mathcal{F}$ is the resonator finesse.[6] For a simple strand of fiber without the effects of resonance ($r = 0$), $\mathrm{d}\phi_{\text{eff}}/\mathrm{d}P_1$ reduces to $2\pi L n_2/\lambda A_{\text{eff}}$. Thus the effect of the resonator is to introduce two separate enhancements for which the combined action on resonance yields an overall nonlinear response that is quadratically enhanced by the finesse.[7]

The enhanced effective phase shift can lead to important consequences. For instance, by introduction of the ring resonator into one arm of a Mach–Zehnder interferometer, as in Fig. 1(b), the phase-switching characteristics are made manifest as power-switching characteristics, and thus we can construct an all-optical switching device with a lowered threshold. In Fig. 3 we compare the transmission characteristics for the standard and the resonator-enhanced nonlinear Mach–Zehnder interferometers for $\lambda = 1.55\ \mu$m and negligible attenuation. The transmission for a standard nonlinear Mach–Zehnder interferometer with unbalanced path lengths ($\Delta L = 10$ m), plotted versus incident power in Fig. 3(a), exhibits a switching threshold of 240 W. Figure 3(b) shows the transmission of a resonator-enhanced Mach–Zehnder (REMZ) interferometer with a ring length of 10 m and a reflectivity of 0.99. The enhanced device exhibits a switching threshold of approximately 12 mW. Both devices possess the same physical interaction length of 10 m, but the REMZ device that we propose possesses a switching threshold that is greatly reduced by a factor of $(2/\pi^2)\mathcal{F}^2 = 20{,}000$.

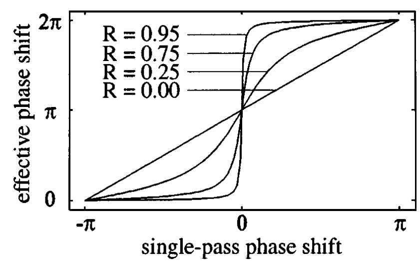

Fig. 2. Effective phase shift $\phi_{\text{eff}} = \arg(E_3/E_1)$ versus the ring single-pass phase shift ϕ for the fiber ring resonator of Fig. 1(a) for several values of $R = r^2$. For values of R close to unity, the phase sensitivity $\mathrm{d}\phi_{\text{eff}}/\mathrm{d}\phi$ can be made extremely large.

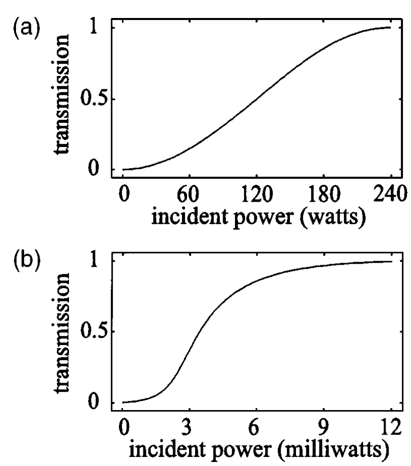

Fig. 3. Transmission characteristics of (a) a standard nonlinear Mach–Zehnder interferometer and (b) the REMZ interferometer of Fig. 1(b). Note that the switching threshold of the REMZ device is lowered by 4 orders of magnitude.

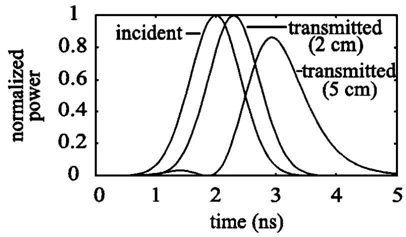

Fig. 4. Ring resonator dynamic transmission characteristics for a 1-ns FWHM Gaussian pulse that is incident upon two distinct fiber ring lengths (2 and 5 cm), corresponding to resonator lifetimes of 1 and 2.5 ns for a resonator of finesse equal to 10.

There are many undesirable effects that can limit the performance of the enhancing ring resonator. We have studied the effects of attenuation, partial source coherence, time-varying input fields, thermal nonlinearity, intensity-dependant nonlinearity in the directional coupler, and optical bistability on the enhancing properties of the ring resonator. We find that these processes, although they are undesirable, do not prevent the device from displaying the useful enhancement properties described in this Letter. Attenuation in the fiber and in the coupler limits the operation of the device; however, a careful analysis shows that the nonlinear figure of merit, the ratio of effective nonlinearity to absorption, is in fact enhanced linearly proportionally to the finesse. The thermal nonlinear response of an optical silica fiber can be many orders of magnitude larger than the electronic nonlinear response. Fortunately, it possesses a relatively slow response time of the order of milliseconds and thus would not influence the short pulse response of the system.

The inherent transient response time of the resonator limits the operation of the device to a maximum modulation frequency given roughly by the inverse of the cavity lifetime, or equivalently by the full width at half-depth of the resonance peak ($c/n\mathcal{F}L$). For instance, in Fig. 4 we draw a comparison between the temporal responses of ring resonators of two distinct ring lengths (5 and 2 cm) for an incident Gaussian pulse of 1 ns (FWHM) and a resonator finesse of 10. For the 5-cm ring the cavity lifetime is 2.5 times the input pulse width, and as a result the transmitted pulse suffers a significant amount of distortion. By contrast, the shorter 2-cm ring possesses a cavity lifetime that exactly matches the incident pulse width, and the transmitted pulse shape is well preserved. Although it is desirable to have a large overall enhancement factor, the lowering of the cutoff frequency inversely proportionally to $\mathcal{F}L$ will accordingly limit the frequency response to the device.[8,9] However, because the overall enhancement factor scales quadratically with the finesse, proportionally to $\mathcal{F}^2L$, any desired enhancement and cutoff frequency can be obtained in principle, provided that the resonator can be made to small dimensions (lower L) and with large enough finesse (higher $\mathcal{F}$). We note that ring resonators have been constructed at the scale of micrometers by use of integrated optics.[10,11] In particular, values of the finesse larger than 10^6 have been observed in the resonance features associated with the whispering-gallery modes of microresonators.[12,13] Owing to their small dimensions and high finesse, coupling these resonators to an interferometer would provide large nonlinear phase-shift enhancements while maintaining high-speed switching characteristics.

In conclusion, we have demonstrated that the nonlinear phase-transfer characteristics of a fiber ring resonator can exhibit an overall enhancement proportional to resonator finesse squared. We have also shown that such devices can be used to construct all-optical switching devices with silica optical fibers that operate at milliwatt power levels.

This work was supported by the sponsors of the University of Rochester Center for Electronic Imaging Systems and by a National Science Foundation Graduate Fellowship. R. W. Boyd's e-mail address is boyd@optics.rochester.edu.

References

1. M. N. Islam, *Ultrafast Fiber Switching Devices* (Cambridge U. Press, Cambridge, 1992), pp. 31, 39.
2. L. F. Stokes, M. Chodorow, and H. J. Shaw, Opt. Lett. **7,** 288 (1982).
3. C. K. Madsen and G. Lenz, IEEE Photon. Technol. Lett. **10,** 994 (1998).
4. J. Capmany, F. J. Fraille-Pelaez, and M. A. Muriel, IEEE J. Quantum Electron. **30,** 2578 (1994).
5. B. Crosignani, B. Daino, P. Di Porto, and S. Wabnitz, Opt. Commun. **59,** 309 (1986).
6. Here the finesse is defined as the free spectral range divided by the full width at half-depth of the resonance peak. Applying this definition to the intensity magnification [Eq. (3)], we calculate the finesse as

$$\mathcal{F} = \frac{\text{FSR}}{\text{FWHD}} \xrightarrow[ra\delta \to 1]{} \frac{\pi}{2} \frac{1 + ra\delta}{1 - ra\delta}.$$

   Here, a is the single-pass amplitude transmission and δ is the degree of coherence between fields delayed by the ring transit time (see Refs. 14 and 15, below).
7. A finesse-squared enhancement has been observed in the context of fiber-optic squeezed light generation in a fiber ring resonator. See, for instance, R. M. Shelby, M. D. Levenson, D. F. Walls, and A. Aspect, Phys. Rev. A **33,** 4008 (1986); R. M. Shelby, M. D. Levenson, and S. H. Perlmutter, J. Opt. Soc. Am. B **5,** 347 (1988).
8. B. Crosignani, A. Yariv, and P. Di Porto, Opt. Lett. **4,** 251 (1986).
9. G. S. Pandian and F. E. Seraji, Proc. IEE Part J **138,** 235 (1991).
10. F. C. Blom, D. R. van Dijk, H. J. Hoekstra, A. Driessen, and Th. J. A. Popma, Appl. Phys. Lett. **71,** 747 (1997).
11. B. E. Little, S. T. Chu, and H. A. Haus, Opt. Lett. **23,** 894 (1998).
12. J. Popp, M. H. Fields, and R. K. Chang, Opt. Lett. **22,** 1296 (1997).
13. N. Dubreuil, J. C. Knight, D. K. Leventhal, V. Sandoghdar, J. Hare, and V. Lefevre, Opt. Lett. **20,** 813 (1995).
14. Y. Ohtsuka, J. Lightwave Technol. **LT-3,** 378 (1985).
15. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge U. Press, Cambridge, 1995), pp. 52–59.