Transmission of a broadband light through a fiber optic loop: effect of nonlinear refractive index

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Abstract: The results of studies of broadband light transmission through a fiber loop and a double loop under the effect of nonlinear refractive index are presented in this paper. Fiber loop and double loop transmission/reflection vs. a coupler splitting ratio at various powers of the light with a spectral width of approximately 35 nm are studied and high efficient nonlinear light switching is demonstrated. It is shown that a double loop formed by consecutive connecting 2 fiber loops allows us to exclude the strong spectral dependence of light transmission/reflection and to distribute input light equally between them. Such all-fiber devices can find a real application in broadband systems of optical communication and data processing.

Key words: Fiber loop, double loop, directional coupler, optical Kerr effect, nonlinear optical switch

1. Introduction

The unprecedented progress in optical communication and data processing systems during the last decades using optical fibers with signal transmission rates up to 1 Tb/s makes it important to develop a new generation of functional elements with essentially higher speeds [1]. One of the key decisions regarding this problem concerns all-fiber optical elements made of single-mode fibers [2]. Technologies for manufacturing fiber directional couplers at present allow the design of all-fiber elements with additional losses $\leq 0.1\,\mathrm{dB/km}$ [3,4].

The specific feature of light propagation in an optical fiber favorable for nonlinear effects is extremely high intensities of a light to be reached in such a guiding medium even at moderate powers; at input power of 1 W the light intensity in a single mode fiber with core diameter of $5\,\mu\mathrm{m}$ exceeds $1\,\mathrm{MW/cm}^2$. Moreover, throughout all fiber length the light profile, phase, and polarization are preserved, which creates unique physical conditions for studying nonlinear effects and developing principally new types of functional elements, using nonlinear processes in fibers [5–7].

A fiber loop or fiber Sagnac interferometer, depending on its parameters, may be employed as a mirror, a spectral filter, or a switcher in a nonlinear regime [8–10]. The fiber loop has also shown a unique property to select optical solitons from a nonsolitonic background in the light generated by nonlinear effects in fibers [11,12]. However, the strong spectral dependence of a splitting ratio of a coupler, specific for devices based on coupled waves [13], essentially limits the possibilities of employing of a fiber loop as a functional element in broadband optical communication and data processing systems.

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In a double loop formed by consistently connecting 2 directional couplers [14] and having long (~ 1 km) contours of a polarization maintaining fiber, the nonlinear switching of a narrow band CW light in the spectral division nearby $1.5\,\mu$m has been observed and attributed to nonlinear walk-off in the phases of orthogonally polarized waves. In that work it has been observed that transmission of the double loop studied, as in a single loop, strongly depends on light wavelength. In [15] we have experimentally demonstrated that spectra of reflected and transmitted fractions of an ultra-broadband IR light ($1.1 - 1.6\ \mu$m) of ~ 100 ps pulses entered in a short contour double loop ($1 - 2$ m) are practically identical, irrespective of light power.

In the present work, spectral and power dependences of a broadband light reflection and transmission through a fiber loop and a double loop are analyzed and experimentally studied. Perspectives for application of such fiber elements in broadband systems of optical communication and data processing are discussed.

2. Experimental set-up

Fiber loops and double loops studied were made of $(SiO_2 + GeO_2)/SiO_2$ type optical fiber with core/cladding diameters of $6\,\mu$m / $125\,\mu$m and refractive indexes difference of $6.8 \cdot 10^{-3}$. Directional couplers were made by fusing and taping of a small site of 2 closely placed fiber pieces, where efficient energy transfer between cores of the fibers takes place due to the optical coupling between the evanescent tail of modes of one fiber in which light is launched and the guiding mode of another fiber [16]. At real technological parameters of such couplers, complete (100%) transfer of a light from one fiber to another occurs at a beat length of $L_b \approx 1$ cm and is characterized by a periodic dependence on coupling length (L_{co}) and operation wavelength (λ) [17]. In the loops studied L_{co} was also maintained at ~ 1 cm.

The length of a fiber contour (L) connecting 2 exit ports of a coupler to form a fiber loop may, in principle, vary from tens of centimeters to 1 kilometer and more, and so in all cases $L_{co} \ll L$. This circumstance allows simplifying analysis of a nonlinear regime of light transmission through a fiber loop essentially, considering that nonlinear interaction occurs only in a fiber contour, and interference only in a coupler [18].

A fiber double loop was formed by connecting 2 single loops consistently. Here, the simplest case for analysis is that when both couplers split a light intensity equally with ratio $\alpha = 0.5$ and optical paths of 2 counter-propagating waves passing through 2 fiber pieces between 2 couplers should be absolutely equal. However, in reality, fiber coupler technologies (for example, splicing/taping) do not allow these conditions to be maintained. In commercially available couplers, light splitting ratio and its spectral dependence may slightly vary from sample to sample ($\sim 1\%$) and equality of lengths of 2 fiber pieces between couplers may be controlled with accuracy of ~ 1 mm. In addition, there is another mechanism of optical paths' inequality related to uncontrolled variations of a fiber core/cladding diameter having technological origin [3]. Fiber core/cladding diameter variations bring about relevant variations in guiding characteristics, particularly, light propagation constant, β. If core diameters of the 2 fibers with length of $L = 1$ m differ for 0.5% ($\Delta d_{co}/d_{co} = 5 \cdot 10^{-3}$), in assumption of linear dependence of $\beta(d_{co})$ in the vicinity of $V = 2.405$ [13], the difference in their optical paths may be defined as:

$$\Delta L = (\Delta\beta/\beta)L = \Delta n(\Delta d_{co}/d_{co})L = 6.8 \cdot 10^{-3} \times 5 \cdot 10^{-3} \times 1\,\text{m} = 0.034\,\text{mm}$$

Since the fiber loop and double loop studied were made of a fiber with weak birefringence (a fiber with stresses in the cladding area) [19] with $\delta n \sim (2 \div 5) \cdot 10^{-8}$ (measured in straight fiber pieces), taking into account short lengths of loops, $1 - 2$ m, walk off in the phases of 2 orthogonally polarized waves may be neglected.

The principal scheme of the experimental set-up is shown in Figure 1. A CW pumped Q-switched+mode-locked Nd^{3+}: YAG laser ($\lambda = 1.064\,\mu m$, $P_{pulse} = 200\,kW$, $\tau_{pulse} = 100\,ps$, $f = 1\,kHz$) was used as source of a pump light (1) and a low intensity He–Ne laser (1.15 μm) for control of the polarization properties of the fiber loop (2). The pumping light generated a light continuum in low-mode fiber (3) with $L = 20\,m$, $d_{co} = 10\,\mu m$ under simultaneous action of several nonlinear effects of third order nonlinearity [16]. The light continuum was an ultra-broadband radiation with pulse duration of $< 100\,ps$ extended in the spectral range of $1.1-1.6\,\mu m$ [20]. The presence of higher order guided modes and the possibility of 4-wave mixing of different spectral components of the light continuum [21] in the fiber generator exclude distinguished formation of stimulated Raman scattering (SRS) solitons, simplifying the analysis of nonlinear light transmission in a fiber loop neglecting soliton effects [18]. The fiber generator of the light continuum is a convenient source of an ultra-broadband light operating at moderate laser powers, and at higher powers a light continuum may be generated in other types of nonlinear media [22]. A narrower band (approx. $\Delta\lambda = 35\,nm$) light of relevant intensity was formed by cutting off the light continuum using wavelength-selective multilayer dielectric (4) and broadband dielectric (5) mirrors. This light entered and exited the fiber loop (or double loop) (6) by means of microlenses (7). Parameters of the light waves reflected and transmitted through a fiber loop (double loop) were measured with avalanche photo diodes (8) and oscilloscope (9), and light pulse energy with a powermeter (10). Light spectra were measured with a monochromator (11), high sensitive germanium photodetector (12), and boxcar integrator (13), and registered by " $X - Y$ " recorder (14).
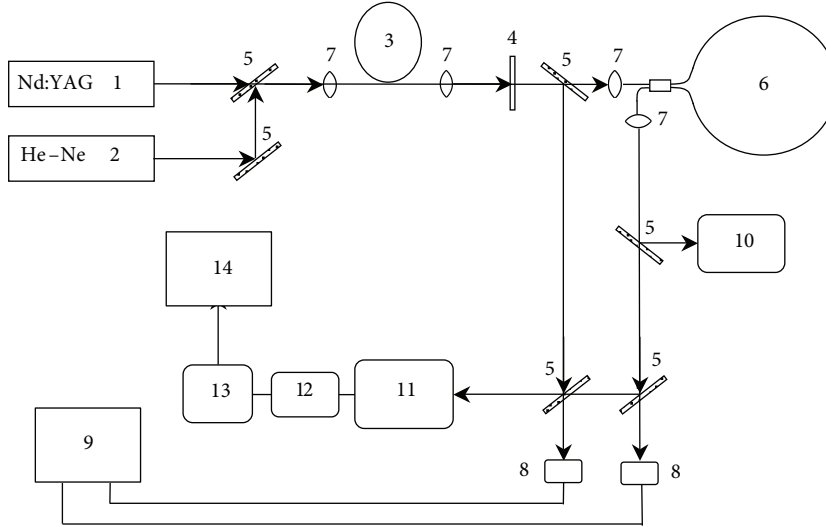
Figure 1. Schematic diagram of the experimental set-up (explanations in the text).

3. Light transmission through a fiber loop

Let us consider light passage through a fiber loop. The light with amplitude of A_0 ($A_0 = I_0^{1/2}$, where I_0 - light intensity) entering a fiber loop through one of its input ports is split at the coupler into 2 counter-propagating waves. If the coupler's splitting ratio is α (in terms of intensity), the amplitudes of 2 counter-propagating waves in the clockwise and counterclockwise directions are defined, accordingly:

$$A_{cw} = I_{cw}^{1/2} = (\alpha I_0)^{1/2} = \alpha^{1/2} A_0 \tag{1}$$

and

$$A_{ccw} = (-I_{ccw})^{1/2} = [-(1-\alpha)I_0]^{1/2} = i(1-\alpha)^{1/2}A_0 \tag{2}$$

Note that the wave A_{ccw} obtains an additional phase of $90°$ in the coupler when it crosses from one fiber to another [13]. These 2 waves passing along the fiber contour in 2 opposite directions obtain the same phase shifts (in the case of lack of Sagnac effect and/or nonlinear effects their optical paths are identical) [23,24] and once again interfere in the coupler. Thus, the amplitudes of waves leaving the fiber loop through the port via light that enters (reflected wave) and through another one (transmitted wave) are, accordingly:

$$A_{rf} = \alpha^{1/2}A_{ccw} + i(1-\alpha)^{1/2}A_{cw} = i[\alpha(1-\alpha)]^{1/2}A_0 + i[\alpha(1-\alpha)]^{1/2}A_0 = 2i[\alpha(1-\alpha)]^{1/2}A_0 \tag{3}$$

and

$$A_{tr} = \alpha^{1/2}A_{cw} + i(1-\alpha)^{1/2}A_{ccw} = \alpha^{1/2}\alpha^{1/2}A_0 + i^2(1-\alpha)^{1/2}(1-\alpha)^{1/2}A_0 =$$

$$= \alpha A_0 - (1-\alpha)A_0 = (2\alpha - 1)A_0. \tag{4}$$

Note that the transmitted wave retains the same phase as the input wave, and the reflected one is shifted by $90°$.

At high intensities of entering light one should consider the effect of nonlinear refractive index induced by self-phase modulation (SPM) and cross-phase modulation (XPM) [21]. In the conditions of our experiment due to ultrashort light pulses ($\tau_p < 100\,\mathrm{ps}$) were used counter-propagating waves that interact in a very small distance ($< 1.5\,\mathrm{cm}$), and thus the nonlinear phase induced by a counter-propagating wave, XPM, is much less than that in the own field of a wave, SPM. The nonlinear phase induced by SPM is [25]:

$$\Delta\varphi = (2\pi n_2|A|^2 L)/\lambda A_{eff}, \tag{5}$$

where $n_2 = 3.2 \cdot 10^{-16}\mathrm{cm}^2/\mathrm{W}$ denotes the nonlinear refractive index coefficient of fused quarts, $A_{eff} = \pi(d_{eff}/2)^2$ is the effective area, and d_{eff}-diameter of a light spot in a single mode fiber (d_{eff} increases approx. 1.5 times when wavelength increases from 1.1 to 1.6 μm [5]).

When $A_{cw} = A_{ccw}$ nonlinear phases of 2 counter-propagating waves are equal to each other and amplitudes of reflected and transmitted waves according to formulae (3) and (4) are: $A_{rf} = 2i[\alpha(1-\alpha)]^{1/2}A_0 = 2i[0.5 \times (1-0.5)]^{1/2}A_0 = iA_0$ and $A_{tr} = (2\alpha - 1)A_0 = (2 \times 0.5 - 1)A_0 = 0$, i.e. the fiber loop completely reflects a light irrespective of its power.

Nonlinear phases of the 2 counter-propagating waves may be different only when $\alpha \neq 0.5\,(A_{cw} \neq A_{ccw})$. In a nonlinear regime the amplitudes of these 2 waves taking into account formula (5) may be defined as:

$$A'_{cw} = A_{cw}\,exp(i\varphi_0 + i\gamma|A_{cw}|^2 L) \tag{6}$$

and

$$A'_{ccw} = A_{ccw}\,exp(i\varphi_0 + i\gamma|A_{ccw}|^2 L). \tag{7}$$

Here φ_0 denotes a linear phase and $\gamma = 2\pi n_2/\lambda A_{eff}$ is a nonlinearity coefficient. Then the amplitudes of reflected and transmitted waves are, respectively:

$$A_{rf} = \alpha^{1/2}A'_{ccw} + i(1-\alpha)^{1/2}A'_{cw} \tag{8}$$

and

$$A_{tr} = \alpha^{1/2} A'_{cw} + i(1 - \alpha)^{1/2} A'_{ccw}. \tag{9}$$

Finally, nonlinear transmission of a fiber loop is:

$$\beta \equiv P_{tr}/P_0 = |A_{tr}|^2/|A_0|^2 = 1 - 4\alpha(1 - \alpha)\{cos^2[(\alpha - 1/2)\gamma|A_0|^2 L]\}. \tag{10}$$

According to formula (10) at $\alpha = 0.5$ transmission of a fiber loop is equal to 0 in a nonlinear regime, as discussed above. However, now, even when $\alpha \neq 0.5$, if $(1 - 2\alpha)\gamma|A_0|^2 L = (2k - 1)\pi$ the fiber loop completely transmits a light. In this case, at low intensities, when $(1 - 2\alpha)\gamma|A_0|^2 L \ll \pi$ formula (10) becomes sufficiently simpler: $\beta = 1 - 4\alpha(1 - \alpha) = (2\alpha - 1)^2 = \beta_0$. In this way, initially low linear transmittance of a fiber loop may be increased dramatically (up to 100%) under the light of a definite power. Such a phenomenon, named light switching, has interesting prospects to be employed in functional elements in optical communication and data processing systems [1].

In Figure 2 the fiber loop transmission vs. light wavelength, $\beta(\lambda) = P_{tr}/P_0$, at different input powers is shown. The solid line corresponds to the function cos^2x adjusted to experimentally measured values of transmission at low powers, $\beta_0(\lambda)$ ($A_0 < 10\,W$, closed circles). With increasing of light power the $\beta(\lambda)$ plot becomes different from $\beta_0(\lambda)$ (open circles, $A_0 = 220\,W$), but in the vicinity of $\alpha = 0.5\,\beta(\lambda)$ is still near to 0. Further increasing of A_0 brings about much stronger changes in $\beta(\lambda)$, and the ratio $\beta(\lambda)/\beta_0(\lambda)$, the switching coefficient, conventionally used for quantitative estimation of transmission changes, reaches values up to 10 (triangles and squares, at $A_0 = 505\,W$ and $950\,W$, respectively). Thus, under the effect of nonlinear refractive index the spectrum of linear transmission of a fiber loop $\beta_0(\lambda) \sim cos^2(\lambda)$ is dramatically transformed, still being near to zero in the vicinity of $\alpha = 0.5$.
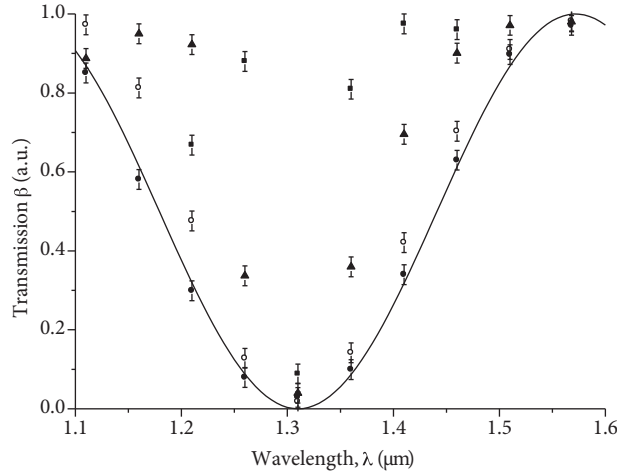
Figure 2. Fiber loop transmission (β) vs. a light wavelength. Solid line is the calculated dependence (function cos^2x); closed circles, open circles, triangles, and squares are β values measured at light powers of $10\,W$, $220\,W$, $505\,W$, and $950\,W$, respectively.

$P_{tr}(A_0)$ dependences in a fiber loop calculated using formula (10) at various α are shown in Figure 3. The solid line corresponds to complete transmission of a fiber loop ($\beta = 1$, $\alpha = 0$ or 1). At strong asymmetric splitting, $\alpha = 0.96$, the $P_{tr}(A_0)$ function (dashed line) has a small periodic fraction (nonlinear

transmission), which is in an area between 2 straight lines corresponding to $\beta = 1$ and $\beta = \beta_0$. Triangles show the measured dependence $P_{tr}(A_0)$ for this case (at $\lambda = 1.11\,\mu m$). When α approaches 0.5, the function $P_{tr}(A_0)$ is dramatically changed: at low powers transmission is near 0, but, with increasing of A_0, P_{tr} rapidly increases and at a critical power A_0^{crit}, it reaches $A_0\,(\beta = 1)$. The dashed-dotted line and open circles in Figure 3 correspond to calculated plot and experimental data for the case of $\alpha = 0.64$ (at $\lambda = 1.26\,\mu m$) with switching coefficient, β/β_0, up to 10, accordingly. A_0^{crit} in this case is 1400 W.
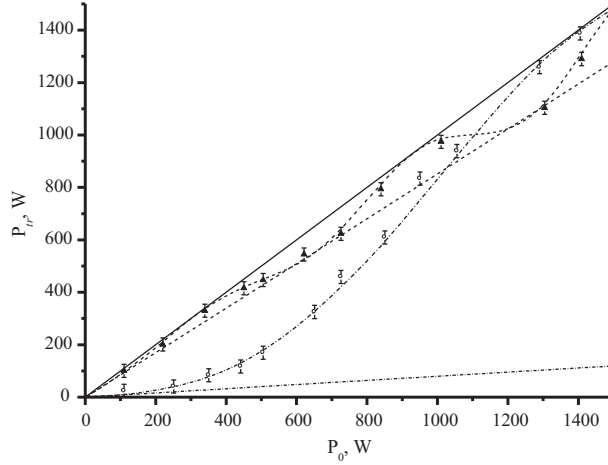
Figure 3. $P_{tr}(P_0)$ plot in a fiber loop calculated using formula (10) at 2 different values of α. In the entire range of P_0 the periodic function $P_{tr}(P_0)$ is between the 2 straight lines: the solid line corresponds to complete transmission ($\beta = 1$) and linear transmission ($\beta = \beta_0$); the dashed and dashed-dotted straight lines correspond to $\alpha = 0.96$ and 0.64, respectively. Relevant data measured experimentally are shown by triangles and open circles.

Thus, in the vicinity of the point $\alpha = 0.5$ where linear transmission of the fiber loop is low, efficient light switching may occur at high powers. Decreasing of the critical power for complete transmission by means of increasing fiber loop length brings about the appearance of other competing nonlinear processes. The most probable and significant one among them from the point of interference to light switching is SRS. SRS threshold depends on a light power and physical conditions of light propagation in a fiber. Neglecting polarization effects and influence of spectral width of a light, one can calculate the SRS threshold power in our experimental case ($L = 2\,m$, $\alpha \approx 0.5$, $d_{co} = 6\,\mu m$) as $P_{ths} \approx 5\,kW$ [16]. Light switching in a fiber loop will be efficient if the power of the light is below this threshold. When α approaches 0 (or 1) the SRS threshold decreases 2 times, while P_0 also decreases in accordance with formula (10).

4. Light transmission through a double fiber loop

Analysis of light passage through a double fiber loop in terms of 2 counter-propagating waves is rather complicated. We will consider, for simplicity, the case when 2 couplers of a double loop have identical splitting ratios, α (Figure 4).

Unlike a conventional laser light with a narrow spectral line ($\Delta\lambda \leq 0.1\,nm$), the light with spectral width of $\sim 35\,nm$ used in our experiments has very short coherent length, $l_{coh} \sim 50\,\mu m$, which is much less than real values of the difference in optical paths between 2 couplers (in commercially available loops this difference may be as much as $\sim 1\,mm$). Therefore, 2 light waves counter-propagating through a fiber loop in the clockwise and

counterclockwise directions will not interfere in the second coupler, but independently split into 2 components each, in accordance with the splitting ratio, α. Further, in the second fiber loop 2 counter-propagating waves consist of 2 components not mutually correlating in phases. The last circumstance indicates the necessity of considering intensities of counter-propagating waves (I_i) instead of their amplitudes (A_i).
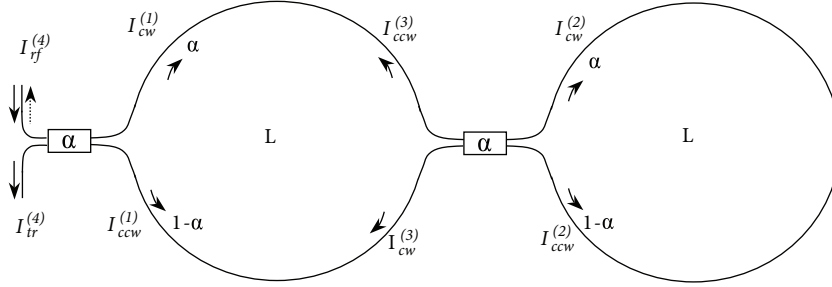
Figure 4. Consecutive passage of light waves through a double fiber loop.

In the first coupler the light of intensity I_0 is split into 2 waves of intensities $I_{cw}^{(1)} = \alpha I_0$ and $I_{ccw}^{(1)} = (1 - \alpha) I_0$, and after the second coupler 2 counter-propagating waves of intensities $I_{cw}^{(2)} = 2\alpha(1 - \alpha) I_0$ and $I_{ccw}^{(2)} = [\alpha^2 + (1 - \alpha)^2] I_0$ are formed (Figure 4). These 2 waves having passed through the second loop and once again second coupler (in the opposite direction) form, in their own turn, 2 counter-propagating waves of intensities $I_{cw}^{(3)} = \alpha (4\alpha^2 - 6\alpha + 3) I_0$ and $I_{ccw}^{(3)} = (1 - \alpha)(4\alpha^2 - 2\alpha + 1)I_0$. Finally, on the exit of the double loop, intensities of waves in 2 ports (reflected and transmitted waves) will be:

$$I_{rf}^{(4)} = \alpha(1 - \alpha)(8\alpha^2 - 8\alpha + 4)I_0$$

and

$$I_{tr}^{(4)} = \alpha^2(4\alpha^2 - 6\alpha + 3) + (1 - \alpha)^2[4\alpha^2 - 2\alpha + 1] I_0.$$

At low intensities, when it is possible to neglect the effect of nonlinear index, amplitudes of the 2 counter-propagating waves during consecutive passage of couplers become gradually equal. In Figure 5 the dependences $I_{cw}^{(1)}/I_0$, $I_{cw}^{(2)}/I_0$, $I_{cw}^{(3)}/I_0$, $I_{rf}^{(4)}/I_0$, and $I_{ccw}^{(1)}/I_0$, $I_{ccw}^{(2)}/I_0$, $I_{ccw}^{(3)}/I_0$, $I_{tr}^{(4)}/I_0$ on α are shown. The diagrams clearly show that the above-mentioned gradual balancing of the intensities of 2 counter-propagating waves takes place even at a considerable deviation of α from 0.5. However, lack of coherence between the 2 waves leads to simple scalar adding of intensities of various components of counter-propagating waves, which, in its own turn, results in equalizing of intensities of reflected and transmitted waves.

Thus, unlike a single fiber loop having periodic dependence of light transmission vs. wavelength, a double loop may be employed as a mirror with transmission as well as reflection coefficient of 0.5 in a wide range of wavelengths, excluding only the vicinity of the point $\alpha = 0.5$. This feature of a double loop opens wide prospects for the development of a variety of fiber functional elements based on this interferometric device.

Nonlinear phases of the 2 counter-propagating waves in a double loop due to lack of coherence between them do not result in respective periodic changes in transmission/reflection as take place in a single loop. Therefore, a light switching effect between transmission and reflection should not be observed irrespective of light power. However, in our experiments, in the case of strong asymmetry of the coupler's splitting, when α was close to 0 (or 1) small periodic changes in transmitted and reflected waves with amplitude of 5%–10%
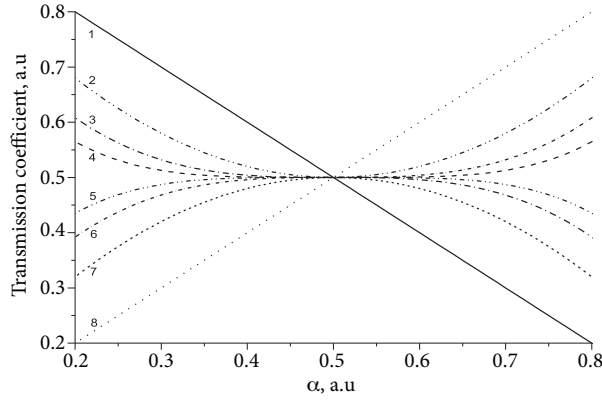
Figure 5. Intensities of the 2 counter-propagating waves in different sites of a double loop, $I_{ccw}^{(1)}/I_0 \quad - \quad I_{tr}^{(4)}/I_0$ (1 - 4) and, $I_{cw}^{(1)}/I_0 \quad - \quad I_{rf}^{(4)}/I_0$ (5–8) (see designation of waves in Figure 4) vs. the splitting ratio of couplers, α.

were observed. These periodic changes in the double loop transmission may be related to interference of 2 orthogonally polarized waves, arising due to the fiber bend origin birefringence [26]. This assumption may be explained as follows. Initial birefringence in free pieces of fiber studied was very low ($\delta n \sim 2 - 5 \cdot 10^{-8}$), and the beat length of orthogonally polarized modes, $L_b \sim \frac{\lambda}{\delta n} \cong 20 - 50\,\mathrm{m}$, was much longer than loop lengths, $L = 1 - 2\,\mathrm{m}$, and so polarization effects should not affect light propagation. However, the bending of a fiber in a loop may bring about an additional birefringence depending on bending curvature [26]. The study of polarization properties of the double loop at $\lambda = 1.5\,\mu\mathrm{m}$ using a $He - Ne$ laser has revealed small polarization anisotropy, but it was not possible to define whether it was related to couplers or fiber contour bending. The experimental fact that changes in fiber bending curvature bring about periodical changes in light transmission confirms the idea of a fiber bending related polarization anisotropy and its effect on nonlinear light transmission. Thus, at wavelengths $1.15\,\mu\mathrm{m}$ and $1.55\,\mu\mathrm{m}$, when couplers are strongly asymmetric and $\alpha_0 \approx 1$ increasing of fiber curvature induces decreasing of transmission of the double loop: $\Delta\alpha/\alpha_0 = 1.5$ at $A_0 = 400\,\mathrm{W}$. Such notable changes in transmission demonstrate the possibility of efficient switching of a light using interference of orthogonally polarized waves in a double loop. Higher values of switching coefficient in this case may be achieved in double loops with longer fiber contours [27].

5. Conclusion

The presented analysis and experimental results of the study of a broadband light passage through a fiber loop and double loop show that such interferometric devices based on a single mode fiber may be employed as prospective functional elements for broadband systems of high-speed optical communication and data processing because of the specific feature of light propagation in single mode fibers extremely favorable for nonlinear light interaction, as well as the advantages of employing all-fiber schemes. The fiber loop reveals an efficient nonlinear light switch with high switching coefficients. Limitations in application of a fiber loop in broadband optical communication and data processing systems related to spectral selectivity of its transmission/reflection may be overcome in a double loop, which equalizes intensities of reflected and transmitted light. Nonlinear light switching in a double loop with a weak birefringence fiber may be achieved using fiber bend related birefringence.

Acknowledgments

References

[1] Agrawal, G. P. *Fiber-Optic Communication Systems*, 4th ed.; Wiley: Hoboken, NJ, USA, 2010.

[2] Liu, Y.; Tangdiongga, E.; Li, Z.; Zhang, S.; Hill, M. T.; Van Zantvoort, J. H. C.; Huijskens, F. M.; De Waardt, H.; Smit, M. K.; Koopen, A. M. J. et al. *Proc. of SPIE*. **2006**, *6353*, 1–12.

[3] Varghese, S. *Fused Fiber Couplers: Basic Theory and Automated Fabrication*; CUST: Cochin, India, 2011.

[4] Chernysheva, M. A.; Krylov, A. A.; Kryukov, P. G.; Dianov, E. M. *Photonics Technology Letters, IEEE*. **2012**, *24*, 1254–1261.

[5] Agrawal, G. P. *Nonlinear Fiber Optics*, 5th ed.; Academic Press: San Diego, CA, USA, 2012.

[6] Fatome, J.; Pitois, S.; Fortier, C.; Kibler, B.; Finot, C.; Millot, G.; Courde, C.; Lindz, M.; Samain, E. *Opt. Commun.* **2010**, *283*, 2425–2429.

[7] Watanabe, *J. Opt. Fiber Com. Rep.* **2005**, *3*, 1–24.

[8] Boscolo, S; Turitsyn, S. K.; Blow, K. J. *Optical Fiber Technology* **2008**, *14*, 299–336.

[9] Zakhidov, E. A.; Kasymdjanov, M. A.; Kurbanov, S. S.; Khabibullaev, P. K. In *Proceedings of NATO RTA Agency Conference "Complementary of Ladars and Radars"*; Prague, Czech Republic, 22–23 April, 2002; Klemn, R.; Koch, W. Eds.; NATO, Brussels, Belgium, 2002, pp.158–166.

[10] Wang, J.; Zheng, K.; Peng, J.; Liu, L.; Li, J.; Jian, S. *Optics Express* **2009**, *17*, 573–583.

[11] Pottiez, O.; Ibarra-Escamilla, B.; Kuzin, E. A. *Optical Fiber Technology* **2009**, *15*, 172–180.

[12] Zakhidov, E. A.; Zakhidova, M. A.; Kurbanov, S. S.; Nematov, Sh. Q.; Khabibullaev, P. K. *Uzbek Journal of Physics* **2009**, *11*, 95–102.

[13] Black, R.; Gagnon L. *Optical Waveguide Modes: Polarization, Coupling and Symmetry*; McGraw Hill Professional: India, 2010.

[14] Chen, G.; Kang, J. U. *J. Opt. A: Pure Appl. Opt.* **2004**, *6*, 361–371.

[15] Zakhidov, E. A.; Zakhidova, ğ. ğ.; Nematov, Sh. Q.; Khabibullaev, P. K. *Uzbek Journal of Physics* **2007**, *10*, 204–209.

[16] Agrawal, G. P. *Applications of Nonlinear Fiber Optics*; 3rd ed.; Academic Press: New York, NY, USA, 2008.

[17] Bayle, F.; Meunier, J. P. *Applied Optics* **2005**, *44*, 6402–6411.

[18] Khaydarov, D.; Zakhidov, E.; Mirtadjiev, F.; Kuznetsov, A.; Okhotnikov, O. *J. Sov. Lightwave Comm.* **1991**, *1*, 197–206.

[19] Lyngso, K.; Mangan, B. J.; Olausson, C. B.; Roberts, P. J. *Optics Express* **2010**, *18*, 14031–14040.

[20] Watt, R. S.; Kaminski, C. F.; Hult A. *J. Appl. Phys. B* **2007**, *90*, 47–53.

[21] Stolen, R. H. *Journal of Lightwave Technology* **2008**, *26*, 1021–1031.

[22] Kokhkharov, A. M.; Shaynurova, K.; Bakhramov, S. A.; Makhmanov, U.; Zakhidov E. A. *J. Appl. Spectroscopy* **2012**, *78*, 802–810.

[23] Lee, B. H.; Kim, Y. H.; Park, K. S.; Eom, J. B.; Kim, M. J.; Rho, B. S.; Choi, H. Y. *Sensors* **2012**, *12*, 2467–2486.

[24] Malykin, G. B. *Optics and Spectroscopy* **2001**, *91*, 795–800.

[25] Zakhidov, E. A.; Kokhkharov A. M.; Mirtadjiev F. M.; Nematov Sh. Q.; Tadjibaev I. I.; Trunilina O. V.; Yarbekov A. E. *Uzbek Journal of Physics* **2012**, *14*, 326–334.

[26] Drexler P.; Fiala P. In: *Recent Progress in Optical Fiber Research*; Yasin M. Ed., InTech: Croatia, 2012, pp. 127–150.

[27] Pottiez, O.; Kuzin, E. A.; Ibarra-Escamilla, B.; Camas-Anzueto, J. T.; Gutierrez-Zainos, F. *Optics Express* **2004**, *12*, 3879–3887.