Observation of simultaneous fast and slow light

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(Received 3 February 2008; published 19 May 2008)

We present a microresonator-based system capable of simultaneously producing time-advanced and time-delayed pulses. The effect is based on the combination of a sharp spectral feature with two orthogonally-polarized propagating waveguide modes. We include an experimental proof-of-concept implementation using a silica microsphere coupled to a tapered optical fiber and use a time-domain picture to interpret the observed delays. We also discuss potential applications for future all-optical networks.

DOI: 10.1103/PhysRevA.77.053816 PACS number(s): 42.25.Lc, 42.25.Ja, 42.79.Sz

Increasing bandwidth demands are pushing for the development of all-optical circuitry that will be able to quickly and reliably transmit and process vast amounts of data. Precise control of light propagation, such as the ability to advance, delay, or store a pulse transmitted through a waveguide, is a requisite ingredient for optical data processing in photonic circuits [1]. Remarkably, exotic optical phenomena occurring in the presence of strong spectral dispersion such as slow [2] and fast [3] light have been found very useful for achieving these goals, generating a surge of experimental activities aimed at realizing fast or slow light in different media: atomic vapors [2–4], crystals [5], semiconductors [6,7], and microresonators [8–11]. These demonstrations have shown either fast or slow light for a given configuration. Here we introduce a microresonator-based system that is capable of simultaneously producing time-advanced and time-delayed pulses, including an experimental proof-of-concept implementation.

The ability to simultaneously slow and advance pulses of light brings about a new perspective on photonics: one can easily envision applications involving all-optical processing of data headers and data packets where both fast and slow light may be desirable. Time-advanced signals can be used to compensate time delays inevitable in any complex optical-processing network [12]. The appeal of strong spectral dispersion is not limited to the linear properties of light: the resulting high optical energy compression may lead to extraordinary enhancement of nonlinear effects and, one day, to single-photon applications for quantum computing and communications. Our experimental implementation uses a silica microsphere evanescently coupled to a tapered optical fiber [13,14] as the resonator. Light polarization plays an important role in the experiment as the enabling tool for achieving fast and slow light and also provides an additional degree of freedom available for data storage and/or processing.

It has been known for a long time that media with sharp spectral features can modify the group speed of light propagating through them [15], resulting in subluminal or superluminal propagation of pulses. More recently it has also been established that systems where two modes can propagate can also show anomalous dispersion, even in the absence of absorption or reflection [16]. This has been shown in photonic crystals [16,17] and coupled mode systems [18]. Our system combines both approaches, using a coherent linear superposition of two propagating modes where only one of them shows a sharp spectral feature [19,20]. This enables us to produce, out of a single incident pulse, two mutually orthogonal pulses of comparable intensity: one time-delayed and another time-advanced with respect to the incident pulse.

We consider a resonator (microsphere) strongly coupled to a waveguide (optical fiber) and assume that the incoming light is incident with a polarization at 45° from the resonator's natural polarization axis, as indicated in Fig. 1. An analyzer selects the polarization component parallel to the incoming one ($\theta=\pi/4$) or orthogonal to it ($\theta=-\pi/4$). Assuming that only one of the natural polarizations of the fiber-microsphere system exhibits resonant transmission fea-

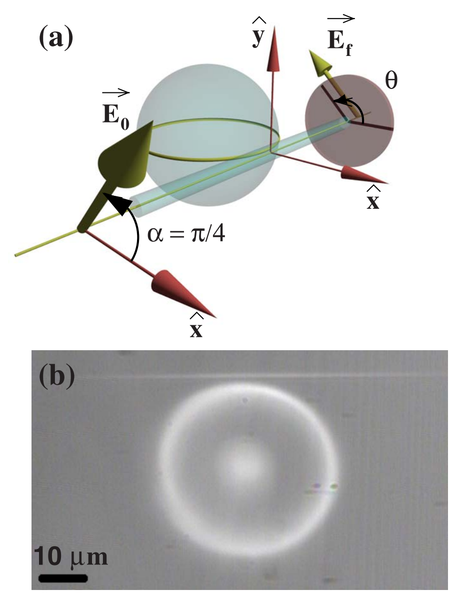

FIG. 1. (Color online) (a) The waveguide supports two degenerate modes with orthogonal polarizations, coincident with the resonator natural polarization axes ($\hat{x}$ and $\hat{y}$). The incident field $\vec{E}_0$ polarization is oriented halfway between the two axes. A polarizer at the output selects either the polarization parallel to the incoming one ($\theta=\pi/4$) or the perpendicular one ($\theta=-\pi/4$). (b) Optical microscope picture showing a microsphere close to a tapered optical fiber.

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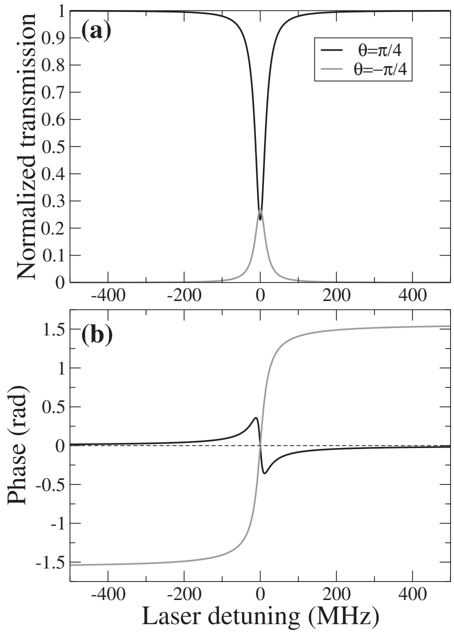

FIG. 2. (a) Calculated transmission spectrum for both detected polarizations in a slightly overcoupled regime (a=0.999 963, r=0.999 960). At resonance, a fraction of the radiation has its polarization rotated by 90°. (b) Phase spectrum for both polarizations. The parallel polarization shows anomalous dispersion near the resonance, while the perpendicular one shows normal but steep dispersion.

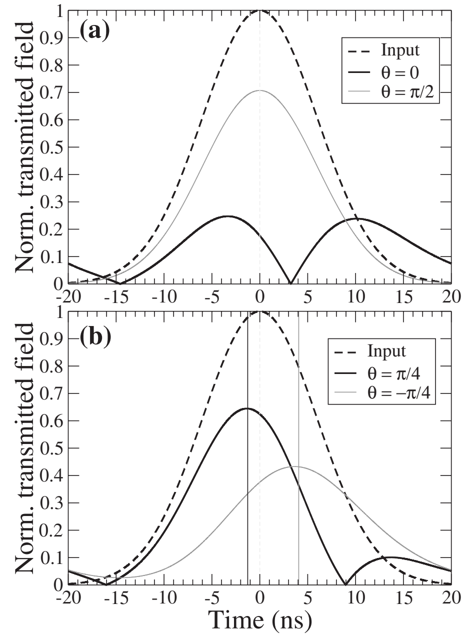

FIG. 3. (a) Calculated transmitted pulses in the resonator natural polarization axes, for the same conditions as in Fig. 2. The θ=0 component is affected by the resonator, while the $\theta=\pi/2$ one is not. The input pulse is polarized along $\theta=\pi/4$. (b) Calculated transmitted pulses for the parallel and orthogonal polarizations. The peak of the parallel pulse is advanced in time, while that of the perpendicular pulse is delayed.

tures, the intensity transmitted through the waveguide can be written for each of the output polarizations as [19]

$$I(\pm\pi/4) = \frac{I_0}{4}(1 + |\tau|^2 \pm 2|\tau|\cos\phi), \tag{1}$$

$$\tau = |\tau|e^{i\phi} = \frac{r - ae^{i\varphi}}{1 - rae^{i\varphi}}, \tag{2}$$

where a and φ are the single-pass resonator attenuation and phase shift, respectively, and $r^2=1-t^2$ with t representing the coupling coefficient between the waveguide and the resonator.

Calculated transmission and phase spectra for each one of the output polarizations are shown in Fig. 2 for the case of a slightly overcoupled resonator. The parallel polarization shows clear absorption and anomalous dispersion at resonance, while the perpendicular one shows gain and normal, but steep, dispersion. Further analysis using vectorial Kramers-Kronig relations [16] suffices to realize that the light coming out with the analyzer set at $\theta=\pi/4$ will show a negative group delay, while there will be a positive group delay for the orthogonal polarization. Using a polarization beamsplitter instead of an analyzer the incoming pulse can be split into two, with one of the child pulses advanced in time and the other delayed.

Previous theoretical work [20] used the frequency-domain approach outlined above to indicate positive and negative group delays are possible for transmission through a waveguide coupled to a resonator, but this is not the only possible approach. The modification of the pulse arrival time can also be explained from a time-domain perspective that matches quite well the time-domain nature of the experimental implementation. In this view, one of the pulse's polarization components is coupled to the resonator [and is thus subjected to dispersion coming from the frequency-dependent transmission coefficient in Eq. (2)] while the other travels straight through the waveguide. The resonator causes the coupled pulse to be temporally distorted [10,21], as shown in Fig. 3(a). The coherent addition of the coupled and uncoupled pulses results in a time-varying polarization at the output. When projecting this polarization into the parallel or orthogonal axis, the detected peak is either advanced or delayed in time with respect to the original one, illustrated in Fig. 3(b) [22].

The ratio between the amplitudes of the advanced and delayed polarizations (as well as the corresponding group delays) can be adjusted by changing the coupling between the resonator and the waveguide. When the resonator is undercoupled, the polarization conversion is weak and the output mostly conserves its original polarization; the negative group delay is small, since the output is dominated by the uncoupled pulse. At critical coupling, both output polarizations are equally transmitted, albeit with a total loss of half the input field. Operation in the strongly overcoupled regime maximizes the negative group delay (temporal advancement) of the parallel polarization and reduces the overall loss. However, very strong polarization conversion [19] significantly reduces the amplitude of the transmitted parallel polarization while maximizing that of the orthogonal polarization. To simplify the measurement, we have chosen an intermediate case of a slightly overcoupled fiber-resonator system.

Changing the input polarization will also result in a different ratio of transmitted amplitudes (and group delays). The largest (both positive and negative) group delays are obtained for an input polarization of 45° at the expense of a somewhat reduced transmission amplitude for the parallel polarized light. For applications where a higher transmission of this component is desirable, using an input polarization of 60° (as suggested in Ref. [23]) would increase this transmission at the expense of smaller achievable group delays. We choose an input polarization of 45° in our experiments to maximize the observable delays and bring them into the range measurable with our existing instruments.

Our experiments were done on a silica microsphere with a 49 μm diameter, fabricated from a single-mode optical fiber using a CO_2 laser. A tapered optical fiber [13,14] acted as the evanescently coupled waveguide (the interaction length between the fiber and the sphere, equivalent to the optical device length, was estimated to be on the order of 10 μm). The coupling strength was controlled by adjusting the relative positions of the sphere and fiber with a piezoelectric stage. Using a tunable diode laser we could find a reasonably sharp resonance, shown in the inset of Fig. 4(a). We estimate this resonance to have mode numbers [24] $l \approx 465$ and $m \approx l$ and an unloaded Q factor near 10^7.

Setting the input polarization approximately at 45°, we sent short Gaussian pulses (full width at half maximum ≈ 8.4 ns) generated by an electro-optic modulator into the fiber. We used a polarizer at the output of the fiber to set the θ analyzer angle at $\pm\pi/4$, and a fast photodiode connected to a digital oscilloscope to record time traces of the field intensity. Proper control of the polarization at the resonator and the output was very important for the experiment, so we used two polarization controllers to compensate for fiber birefringence, one before the resonator and one after it. When the resonator and fiber were brought closer together and the incident light in resonance with the selected mode, the effected group delays were noticeable in the measured traces. Figure 4(a) shows traces for both values of θ together with a reference trace taken with the resonator uncoupled from the waveguide. The pulse peak is advanced 1.35 ns with respect to the reference in the parallel trace, while it is delayed by 4.56 ns in the orthogonal trace. The magnitudes of the changes in the arrival times for both delayed and advanced pulses are much larger than what would be expected for a normal transit time through the device length. From this we can infer that the orthogonal polarization experienced a large group index causing a delay, while for the parallel polarization the peak of the pulse left the resonator before entering it (the corresponding group indices are $n_g^{\perp} \approx 10^5$ and $n_g^{\parallel} \approx -30\,000$). Note that both the delayed and advanced signals are of comparable intensities [25]. Calculations using the time-domain picture, including losses to higher order fiber modes of $\approx 23\%$, show a reasonable agreement with the data.

Both positive and negative group delays are intrinsically narrow-band phenomena, with a bandwidth given by that of the resonant mode. As such, only pulses with a carrier fre-

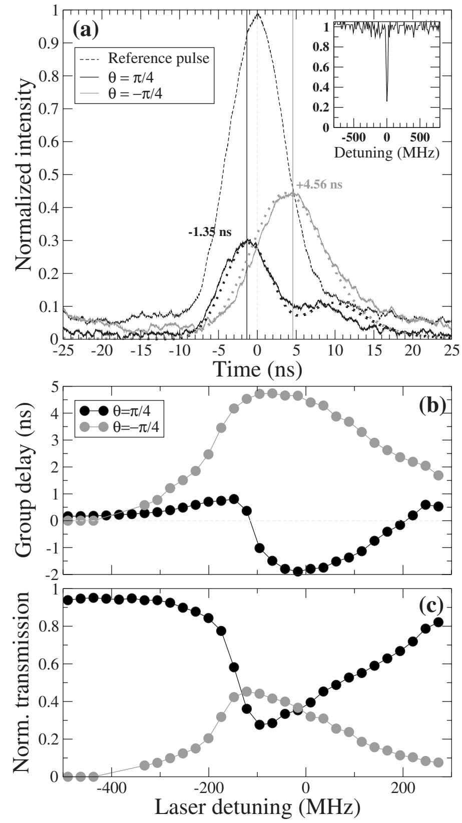

FIG. 4. (a) Measured time traces showing negative and positive group delay polarization angles. The dotted lines represent numerical calculations with estimated attenuation and coupling coefficients $a=0.999\,998$ and $r=0.999\,947$. Inset: spectrum of the unloaded cavity resonance used in the experiments. (b) Observed group delay measured for different laser frequencies. (c) Experimental transmission spectra complementing the group delay data in panel (b).

quency matching that of the mode will be affected. Figure 4(b) corroborates this, showing that the delays become smaller as the laser frequency sweeps away from the resonance center [the corresponding transmissions are displayed in Fig. 4(c)]. Narrow bandwidth is also responsible for some distortion of pulse shapes. As with all passive single-mode-based delay lines, the delay-bandwidth product is limited [26]. Our high-Q resonators maximize the delay at the expense of bandwidth, another choice intended to make the delays measurable with our existing instruments, and thus our bandwidth is too narrow to allow for applications at large modulation rates. Besides, free-standing microspheres are not easy to integrate on photonic circuits. Other resonator systems, such as silica microtoroids [27] or silicon-on-insulator (SOI) microrings [28], could be better suited for integration. In particular, microfabricated SOI resonators have broader linewidths and could work at higher modulation rates (at the expense of smaller induced group delays). Using chains of microfabricated resonators [9,23] might be a way to sidestep that limitation.

The state of the polarization at the resonator is also important to obtain the desired group delays [23]. The theoretical model predicts significant conversion for the overcoupled system when the incoming polarization is at 45°

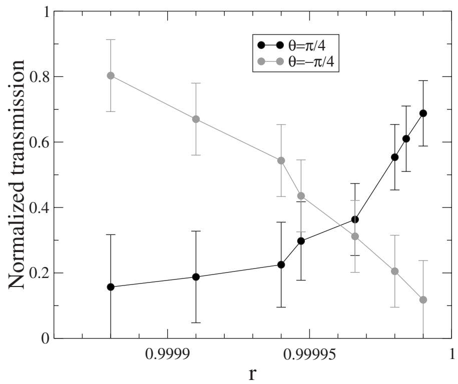

FIG. 5. Experimental polarization conversion for different coupling strengths. Significant conversion is observed as the coupling becomes stronger.

[19], so we use the presence of a strong polarization conversion effect when the coupling increases as an indicator that the polarization at the resonator is close to 45°. We can see in Fig. 5 that the conversion becomes more pronounced as the coupling increases (and r decreases), giving us a confirmation that our incoming polarization is acceptably close to the desired one.

In summary, we have experimentally demonstrated that microresonator-loaded optical fibers can be used to split an incident pulse into mutually orthogonal output pulses experiencing positive and negative group delays. The phenomenon can be explained in both the spectral domain, through generalized Kramers-Kronig relations and the time domain, via a resonator-induced polarization change. This capability could prove useful for the implementation of photonic circuits in all-optical networks, for instance compensating processing-induced delays. Other applications such as single-photon devices for quantum computation and communication are also within the realm of possibilities.

We would like to thank Professor X. Li for useful discussion and her technical help. This work was supported by NSF-NIRT (Grant DMR-0210383), the Texas Advanced Technology program, and the W.M. Keck Foundation. G.S. and C.F. acknowledge support from ARO MURI Grant W911NF-04-01-0203.

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