Whispering Gallery Mode Spool as an Optical Buffer

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Abstract: We discuss designs of photonic systems based on the propagation of light beams with nonzero angular momentum in cylindrical waveguides for applications as all-optical buffers.

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Short chains of coupled planar microring resonators can be used as compact optical buffers, as recently demonstrated.[1] The practical realization of long-chain buffers is nevertheless impeded by the difficulty in the fabrication of identical high-Q resonators, as required in this scheme. Although fabrication of vertically coupled resonator chains[2,3] seems readily achieveble by utilizing diamond turning techniques,[4] the challenge of making equal size resonators still remains unsloved. The goal of the present contribution is to introduce a design for an optical buffer that combines the advantages of vertically coupled resonator chains with the high fabrication tolerances of a conventional cylindrical multimode optical waveguide.

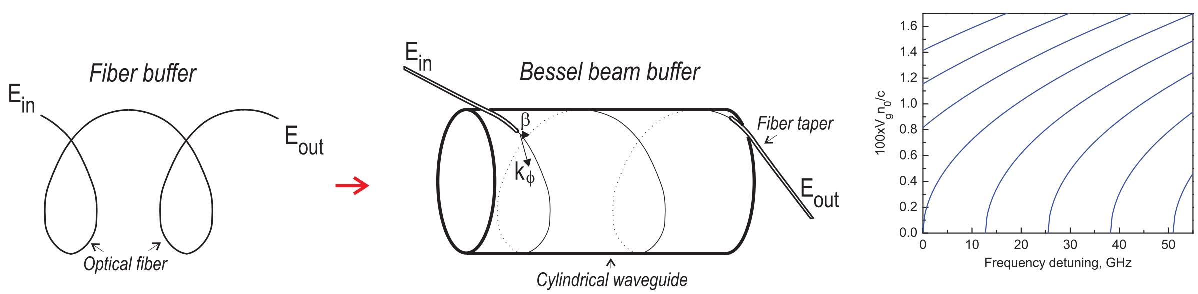

Figure 1. From a spool of optical fiber (left) to a "whispering gallery mode spool" (center). We propose a scheme for coupling light into modes that support propagation in a cylindrical waveguide and result in nonzero angular momenta. The modes have cut-off frequencies and are characterized by a large dispersion (small group velocity) close to those frequencies (right). The waveguide can be used as an efficient delay line not far from the cut-off frequency.

We propose an optical buffer based on the application of Bessel beams, or light modes with nonzero angular momenta, that are able to propagate in a cylindrical waveguide.[5] Such modes, also referred to as spiral morphology-dependent resonances, have been demonstrated in a cylindrical fiber.[6] The modes are localized close to the surface of the fiber, much like the whispering gallery modes. But unlike to whispering gallery modes, they also have a nonzero wave vector along the fiber axis. The Bessel beam optical buffer allows realizing long optical delays, as in chains of vertically coupled resonators, but by a proper design of the in- and out-coupling method could be made to have extremely wide bandwidths as in "white light" structures. An advantage of the buffer is its flexibility to a change in the radius of the cylindrical waveguide. That is, small deviations from the cylindrical symmetry of the waveguide do not lead to a degradation of the performance of this buffer. The buffer has certain similarity with the optical fiber microcoil resonator that consists of self-coupled turns of an optical fiber.[7] However, the morphology of its elements are quite different.

The basic challenge in fabrication of an optical buffer is related to the technique used for in and out light coupling. We propose to use slightly curved fiber tapers to selectively excite the particular modes of interest in the waveguide (Fig. 1). The fiber tapers will interact with the running modes of proper longitudinal propagation constant $\beta_0 + \delta\beta \geq \beta \geq \beta_0 - \delta\beta$ ($\beta_0 \gg 2\delta\beta$) given by the angle between the taper and a plane orthogonal to the axis of the waveguide. The mode trajectories excited with the coupler can be thought of as spirals with the angle $\arctan(\beta/k_\phi)$, where

$$\frac{\omega}{c}n_0 = \sqrt{\beta^2 + k_\phi^2}, \quad k_\phi \simeq \frac{1}{a}\left[\nu + \alpha_q \left(\frac{\nu}{2}\right)^{1/3}\right], \tag{1}$$

and a radius that is approximately equal to the radius of the waveguide a; here ω is the frequency of the light, c is the speed of light in the vacuum, n_0 is the refractive index of the material, ν ($\nu \gg 1$) is the quantum number that determines the angular momentum of the mode, α_q is the qth root of the Airy function $A(-z)$.

The group velocity of light propagating in the modes is given by

$$V_g = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1} = \frac{c}{n_0}\sqrt{1 - \left(\frac{k_\phi c}{\omega n_0}\right)^2} = \frac{c}{n_0}\frac{\beta c}{\omega n_0} \ll \frac{c}{n_0}. \tag{2}$$

It approaches zero at cut-off frequency $\omega_{co}(\nu) = k_\phi c/n_0$. The point with zero group velocity is useless for the optical buffering because the dispersion of the group velocity is infinite there. Really,

$$\frac{\partial^2\beta}{\partial\omega^2} \simeq -\frac{n_0}{c\omega_0}\left(\frac{c}{n_0 V_g}\right)^3, \quad \frac{\partial^3\beta}{\partial\omega^3} \simeq 3\frac{n_0}{c\omega_0^2}\left(\frac{c}{n_0 V_g}\right)^5. \tag{3}$$

An optical buffer can be characterized with the maximum rate of bits B, the maximum number of bits simul-

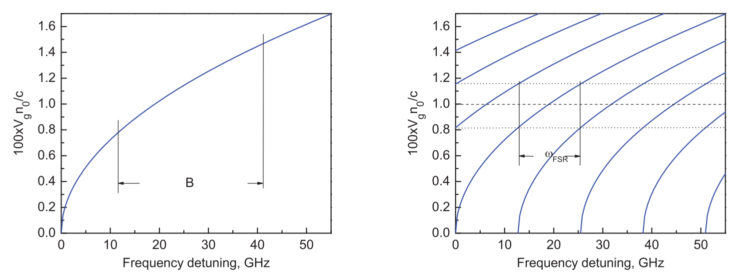

Figure 2. Group velocity dispersion of the Bessel modes. Left: a single mode. The group velocity varies from $0.75V_g$ to $1.5V_g$ for a pulse train characterized with bit rate B and group velocity $V_g n_0/c = 0.012$ at the carrier frequency. Right: Increase of the density of the modes results in decrease of the mode dispersion on pulse propagation.

taneously stored in the buffer N_B, and the buffer geometrical size L. The values are connected by the relation $N_B = BL/V_g$. To evaluate the performance of our buffer we assume that the broadening of a Gaussian pulse due to the buffer dispersion should be small enough. This condition can be quantified as $B(|\beta_2|L)^{1/2} \leq 0.25$ and $B(|\beta_3|L)^{1/3} \leq 0.324$. Let us assume that only one mode in the waveguide is excited (see Fig. 2 Left). Then, the second and third order dispersion place the following restrictions on the buffer parameters:

$$16N_B\frac{B}{\omega_0} < \left(\frac{n_0 V_g}{c}\right)^2, \quad 9.2\sqrt{N_B}\frac{B}{\omega_0} < \left(\frac{n_0 V_g}{c}\right)^2, \tag{4}$$

where ω_0 is the carrier frequency of the optical pulse. These relations show that the slower the pulse is in the buffer the narrower its spectrum would be. To relax conditions (4) one has to excite not just a single mode of the waveguide, but a number of modes. Then, instead of the bit rate, Eqs. (4) will contain the frequency splitting between the modes ω_{FSR}: $B \to \omega_{FSR}$, $B \gg \omega_{FSR}$. The parameter ω_{FSR} corresponds to the free spectral range of a whispering gallery mode resonator, or can be smaller if the coupler excites various families of modes with the same efficiency, as in "white light" whispering gallery mode resonators.[8]

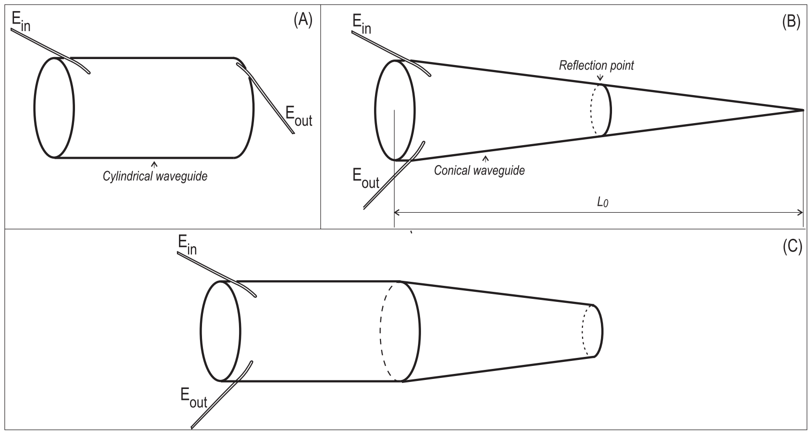

Figure 3. Dispersion management in the buffer. Cylindrical (A) and conical reflecting (B) waveguides have opposite signs of the group velocity dispersion. Combination of them (C) allows one to suppress the second order dispersion.

The dispersion of the group velocity could be suppressed by changing the geometry of the cylindrical waveguide. For instance, the frequency-dependent group delay (τ_g) for a conical reflecting waveguide (Fig. 3(B)) depends on the position of the geometrical reflection point $Z_{refl}(\omega)$ and is equal to

$$\tau_g = 2\int_0^{Z_{refl}(\omega)} \frac{dz}{V_g(z)} = 2\frac{n_0}{c}\int \sqrt{1-\left(\frac{k_\phi c}{\omega n_0}\right)^2 \left(1-\frac{z}{L_0}\right)^{-2}}\, dz = 2\frac{n_0 L_0}{c}\sqrt{1-\left(\frac{k_\phi c}{\omega n_0}\right)^2} \qquad (5)$$

Combining this waveguide with a cylindrical waveguide of length $L = L_0[1 - k_\phi c/(\omega_0 n_0)]$ (Fig. 3(C)), we achieve the suppression of the second order dispersion:

$$\tau_g = 2\frac{n_0 L}{c}\left[\frac{\sqrt{1-\left(\frac{k_\phi c}{\omega n_0}\right)^2}}{1-\left(\frac{k_\phi c}{\omega_0 n_0}\right)^2} + \frac{1}{\sqrt{1-\left(\frac{k_\phi c}{\omega n_0}\right)^2}}\right]. \qquad (6)$$

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