All-single-mode fiber resonator

L. F. Stokes, M. Chodorow, and H. J. Shaw

Edward L. Ginzton Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305

Received February 12, 1982

An all-fiber-ring resonator has been constructed using a single strand of single-mode optical fiber and a directional coupler. Derivation of the resonator finesse in terms of fiber and directional coupler parameters is given. A finesse of 80 has been achieved experimentally. Applications of such a fiber-ring resonator are discussed.

Single-mode optical fiber can be used to make a high-finesse optical resonator by forming a short piece of fiber into a closed ring to constitute a low-loss cavity. With the recent advances in single-mode fiber directional couplers, such a fiber ring can be closed in a low-loss manner.

A schematic of such an optical-fiber resonator is shown in Fig. 1. If the directional coupler has large coupling, light trapped in the fiber ring will couple from port 2 to port 3 and will continue to circulate. Similarly, light introduced to the input port 1 will couple mostly to the output port 4.

Consider the case in which the fiber-loop length is adjusted for constructive interference (addition) between coherent components entering port 3 from ports 1 and 2. The small fraction of light from port 2 to port 4 will destructively interfere with the light coupling from port 1 to port 4. The circulating field will grow until an equilibrium is reached. With an optimum value of coupling that depends on losses, the two destructively interfering components emerging from port 4 are equal in amplitude and completely cancel each other. From an energy-conservation point of view, the circulating power grows until the power dissipated by losses in the loop equals the input power at port 1.

If the light frequency is now varied continuously, the power emerging from port 4 will show a series of sharp minima whenever the input optical frequency matches the resonant condition. The behavior is similar to a Fabry–Perot-type resonator whose reflected power has sharp minima at resonance.

For a resonator of this type to function properly, the directional coupler must have a low insertion loss. As the optimum value of coupling depends on losses, a variable coupling coefficient is desirable. In this experiment, an evanescent-field coupler is used. A single strand of optical fiber is bonded into two slotted quartz blocks a distance \( L \) apart. Each fiber–block unit is ground and polished to within a few micrometers of the fiber core. Placing the two units in contact, oriented as in Fig. 1, produces a ring resonator of perimeter \( L \). Coupler tuning is accomplished by sliding one block over the other to vary the core-to-core separation and optimize the coupling coefficient.

A device similar to this, using a modulated incoherent source, has been demonstrated as a recirculating delay line transversal filter for high-speed signal processing.

The directional coupler is modeled as a perfect (lossless) device with an added lumped loss that is independent of the coupling coefficient. Referring to Fig. 1, the fractional coupler intensity loss \( \gamma_0 \) is given by

\[
|E_d|^2 = |E_2|^2 = (1 - \gamma_0)(|E_1|^2 + |E_2|^2),
\]

where \( E_i \) is the complex amplitude of the fields in the fibers after the coupled-mode interaction are related to the incident-field amplitudes by

\[
E_3 = (1 - \gamma_0)\frac{1}{2}[ (1 - \kappa)^{1/2}E_1 + j\sqrt{\kappa}E_2],
\]

\[
E_4 = (1 - \gamma_0)\frac{1}{2}[ j\sqrt{\kappa}E_1 + (1 - \kappa)^{1/2}E_2],
\]

where \( \kappa \) is the (intensity) coupling coefficient. No coupling corresponds to \( \kappa = 0 \), whereas \( \kappa = 1 \) gives complete cross coupling. \( E_2 \) and \( E_3 \) are further related by

\[
E_2 = E_3 e^{-\alpha_0 L} e^{j\beta L}, \quad \beta = n\omega/c,
\]

where \( \alpha_0 \) is the fiber's (amplitude) attenuation coefficient, \( n \) is the fiber's refractive index, \( \omega \) is the optical frequency, and \( c \) is the speed of light.

Equations (2) and (3) can be solved for \( E_4/E_1 \) in terms of \( \gamma_0, \kappa, \alpha_0 L, \) and \( \beta L \). For a resonant situation we require the real and imaginary parts of \( E_4/E_1 \) to vanish, yielding two necessary resonant conditions. The first is

\[
\beta L = q2\pi - \pi/2,
\]

where \( q \) is any integer. Note that from Eqs. (2) the directional coupler has a \( \pi/2 \) phase shift, so that the total collected phase around the ring is \( 2\pi q \).

![Fig. 1. Schematic of an all-single-mode fiber resonator.](image-url)
The second condition required for resonance specifies the resonant coupling coefficient, denoted by $\kappa_r$:

$$\kappa_r = (1 - \gamma_0)e^{-2\alpha_0 L}. \quad (5)$$

Note that $1 - \kappa_r$ is the round-trip fractional intensity loss.

With this value of coupling, Eqs. (2) and (3) yield the circulating and output intensities:

$$\left| \frac{E_3}{E_1} \right|^2 = \frac{(1 - \gamma_0)(1 - \kappa_r)}{(1 + \kappa_r)^2 - 4\kappa_r \sin^2\left(\frac{\beta L}{2} - \frac{\pi}{4}\right)} \quad (6)$$

$$\left| \frac{E_4}{E_1} \right|^2 = (1 - \gamma_0)$$

$$\times \left[ 1 - \frac{(1 - \kappa_r)^2}{(1 + \kappa_r)^2 - 4\kappa_r \sin^2\left(\frac{\beta L}{2} - \frac{\pi}{4}\right)} \right]. \quad (7)$$

Figures 2(a) and 2(b) show the circulating and output intensities as $\beta L$ is varied. At resonance we have $\sin^2(\beta L/2 - (\pi/4)) = 1$. The output intensity is zero, and the circulating intensity is given by

$$\left| \frac{E_3}{E_1} \right|^2_{\text{max}} = \frac{1 - \gamma_0}{1 - \kappa_r}. \quad (8)$$

The free spectral range (FSR) of the resonator is $c/nL$. By equating Eq. (6) to $\frac{1}{2}|E_3/E_1|_{\text{max}}^2$, the full width at half maximum is found to be

$$\Delta f = c \frac{1}{nL} \left[ 1 - \frac{2}{\pi} \sin^{-1}\left[ 1 - \frac{(1 - \kappa_r)^2}{4\kappa_r} \right]^{1/2} \right].$$

For $\kappa_r$ near unity, $\Delta f$ is, to a very good approximation (within 0.2\% for $\kappa_r > 0.8$),

$$\Delta f \approx \frac{c}{nL} \frac{1 - \kappa_r}{\pi \sqrt{\kappa_r}}.$$

The cavity finesse $F$ is therefore

$$F = \frac{\text{FSR}}{\Delta f} = \frac{\pi \sqrt{\kappa_r}}{1 - \kappa_r}. \quad (9)$$

This is analogous to the finesse of a flat-flat Fabry–Perot étalon, or mirror reflectivity $R$ and spacing $L$, given by $F = \pi \sqrt{R/(1 - R)}$. Note that the étalon and the fiber resonator have a fractional loss per unit length of $(1 - R)/L$ and $(1 - \kappa_r)/L$, respectively.

The cavity decay time can be given approximately as

$$\tau_c \approx \frac{nL}{c\delta},$$

where $nL/c$ is the cavity round-trip time and $\delta$ is the fractional intensity loss per round trip. With no input intensity, the circulating power will decay through the coupler loss ($\gamma_0$), the fiber attenuation ($2\alpha_0 L$), and the output port itself ($1 - \kappa_r$). From Eq. (5), the first two loss mechanisms contribute $1 - \kappa_r$ to $\delta$. Thus

$$\tau_c \approx \frac{nL}{c\delta}.$$
laser (λ = 6328 Å) was used to excite the resonator. A low-frequency triangular wave was applied to the phase modulator, and the output at port 4 was monitored by a photodiode. In this way the fiber resonator behaves like a scanning Fabry–Perot interferometer. The oscilloscope trace of Fig. 4 shows resonant behavior (output power dropping to zero) twice during each linear stretch of the fiber. Although the finesse of Eq. (9) was derived for the circulating intensity maxima, it is clear from Eqs. (6) and (7) that this calculation of finesse applies equally well to the output minima. A finesse of approximately 70 is calculated from Fig. 5. For the highest observed finesse of 80, seen in a separate measurement, Eq. (9) gives κ = 0.962. When a fiber attenuation of −8.3 dB/km at λ = 6328 Å (2aL = 0.0057) is used, Eq. (5) implies a coupler insertion loss of γ₀ = 3.2% (−0.14 dB). It should be noted that the finesse is a sensitive function of coupler loss, so the loss determined here is quite accurate.

The circulating intensity \( |E/E_1|^{2\text{max}} \) is predicted by Eq. (8) to be 25 for the observed finesse of 80. Although this intensity is difficult to measure directly, scattering from the fiber ring was seen easily at resonance, whereas that from the input fiber leading to port 1 was not visible.

Varying the coupler slightly from its resonant coupling coefficient value results in reduced finesse and nonzero output power. By rotating the quarter-wave plates of the polarization controller away from the optimum position, two resonant modes, corresponding to the two independent polarization modes, are observed. As is illustrated in Fig. 5, these two modes resonate at different scanned positions because of slightly different propagation velocities of the two nondegenerate polarization modes.

The art of fabricating low-loss evanescent-field fiber directional couplers is still new. The insertion loss of the coupler used in this resonator, while low, is still significantly higher than scattering loss in several meters of fiber. Further improvements in coupler loss should result in resonator finesse substantially over 100.

Aside from optical-filter and spectrum-analyzer applications, the high-circulating-power enhancement and low cavity loss are ideal for nonlinear optics. For example, a relatively low-power laser could produce a high-power pump in the fiber ring, and stimulated Brillouin\(^5\) or Raman\(^6\) oscillation in the ring should result. The analogous fiber cavities using lenses and mirrors for feedback have round-trip losses of approximately 70%. The fiber ring resonator, with round-trip losses of approximately 5% and inherent pump-power enhancement, should exhibit much lower threshold power for stimulated scattering processes.

The authors wish to thank R. A. Bergh and M. J. F. Digonnet for helpful discussions and J. Feth for the fabrication of the coupler. This research was supported by the Atlantic Richfield Company.

References