Narrow-band Bragg reflectors in optical fibers

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The formation and characterization of narrow-band-waveguide reflection filters in Ge-doped silica optical fibers is described. The filters can have complex response profiles and are tunable in frequency by mechanical strain.

The observation of photosensitivity in the core region of Ge-doped silica optical fibers was recently reported,[1] and this effect was used to produce narrow-band-waveguide reflection filters for the construction of a distributed-feedback gas laser. The filters are apparently permanently induced in the fibers, and we have observed no significant decay or degradation of the devices over periods of several days.

In this Letter, we describe in detail the experimental techniques used to produce and characterize these high-spectral resolution devices. The measurement of the filter characteristics shows that the filters can be made extremely narrow band (<200 MHz). This result is expected, since the filters are formed over long lengths of fiber and are accurately characterized as length-limited Bragg distributed-feedback waveguide filters. Moreover, these devices can be made with multiple rejection bands. An attractive feature of these structures is that they are readily tunable by mechanical strain. These characteristics, together with the compatibility of the devices with optical-fiber systems, make these filters of considerable interest as wavelength-selective devices for optical communications for use, perhaps most notably, in wavelength-multiplexed lightwave-communication systems.

The experimental techniques used to form the fiber-waveguide filters are similar in principle to those used routinely in holographic recording; the beam and apparatus stability requirements are correspondingly high. Figure 1 is a schematic of the experimental arrangement, which is mounted on a floating optical bench in order to ensure the mechanical stability necessary during formation of the Bragg filters. The argon-laser source, oscillating on a single longitudinal mode at 514.5 nm, serves to expose the photosensitive fiber. The output laser beam goes through an attenuator and a 90° reflection before being launched into the fiber by way of the 50X microscope objective. The 50% beam splitter provides an output path along which the backreflected beam from the fiber core can be monitored. Isolation of the argon pump from the destabilizing effects of a backreflected beam is provided by the attenuator and the 50% splitter. We constructed mounts for the fiber following a design intended to provide adequate shielding of the fiber from both thermal and vibrational effects while still permitting the convenient application of a longitudinal tuning stress to the fiber. The input end of the fiber is clamped in the fused quartz jaws of a viselike mount that can be accurately positioned piezoelectrically to permit precise coupling of the argon beam to the fiber. The far end of the fiber is clamped in jaws attached to a section of spring steel, which serves to apply the desired amount of longitudinal stress. The spring also serves to reduce the detuning effects of vibrations that may produce relative motion between the two end mounts. The motion is translated into spring flexure rather than changes in tension on the fiber, as would occur with an inflexible mount. The quartz tube surrounding the fiber shields it from thermal effects that would be induced by air currents around the fiber. Shielding against thermal effects and the minimization of tension changes is necessary in the experiment because the growth of the filters is sensitive to both of these parameters.

The reflection filters described here were grown with

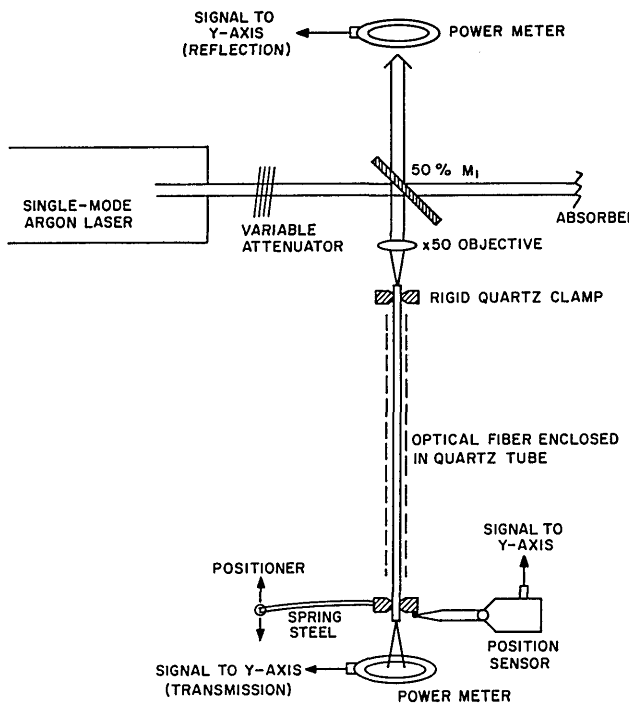

Fig. 1. Schematic of apparatus for producing and measuring fiber filters.

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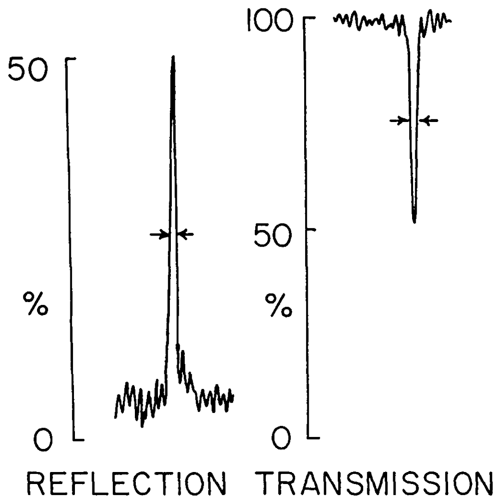

Fig. 2. Typical reflection and transmission spectra for a 62-cm fiber filter. The indicated full width at half maximum is 200 MHz.

the fiber under an initial longitudinal force of a few tens of millinewtons to allow the resonance of the formed filter to be stress-tuned through the fixed wavelength of the argon laser for measurement of the filter's response function. The fiber was exposed to a launched beam of approximately 50 mW at 514.5 nm, and the buildup of the reflection grating was monitored through the 50% mirror. In all of our experiments, after sufficient exposure, the backreflected beam was observed to increase in power by approximately an order of magnitude over the initial Fresnel reflection from the input and output ends of the fiber until a level of saturation was reached. Care was taken to cleave the output end of the fiber at right angles to the fiber axis to provide a 4% reflection in the core to start the buildup of the reflection grating. The Fresnel-reflected beam interferes with the incident primary beam and produces a standing-wave pattern in the fiber to induce the filter formation process. The result is a periodic perturbation of the refractive index of the core along the length of the exposed fiber.

To measure the response of the filter, we replaced the spring mount with a rigid mount, which could be moved piezoelectrically parallel to the axis of the fiber. The axial position of the mount was monitored by an Aerotech position sensor having 0.01-μm resolution, and the position signal was connected to the x-axis input of an x–y recorder. A power meter monitoring either the backreflected beam (reflection) or the beam through the fiber (transmission) provided the y-axis signal. All the experiments described in this Letter were done using a fiber with a Ge-doped core of 2.5-μm diameter and with a fiber numerical aperture of 0.22.

Figure 2 shows reflection and transmission curves for a typical filter formed in a fiber 62 cm long. The filter response is a single narrow peak in both reflection and transmission as the filter is tuned by stretching through the resonance peak, which corresponds to the incident laser wavelength. An average of six recordings of the resonance width gave a value of $\Delta L = 0.294 \pm 0.005\ \mu$m. In the absence of thermal effects and under the assumption that the fiber stretches uniformly over its entire length L, the relation between the frequency bandwidth $\Delta\nu$ and the stretch ΔL is given by

$$\Delta\nu = -\left(1 + \frac{1}{n}\frac{\partial n}{\partial s}\right)\frac{c}{\lambda}\frac{\Delta L}{L}$$

$$\sim -0.414 \times 10^{15}\,\frac{\Delta L}{L} \sim 2.0 \times 10^{2}\ \text{MHz},$$

where n is the index of refraction of the medium, c is the speed of light in vacuum, λ is the vacuum wavelength of illumination, s is strain, and $(1/n)(\partial n/\partial s) = -0.29$ (Ref. 2) is the elasto-optic coefficient. Similar measurements for a filter made in a fiber of 33.5-cm length gives a frequency bandwidth of 3.3×10^2 MHz. These figures can be compared with the bandwidths of length-limited filters given by $\Delta\nu = c/(2nL)$. The bandwidths of filters of 62- and 33.5-cm length are 165 and 306 MHz, respectively. The agreement between the theoretical and measured bandwidth values indicates that each filter was formed uniformly throughout the length of the fiber.

An important property of this filter formation process is the extent to which the filter response can be tailored. One method of forming a complex filter is to superimpose two or more simple band-stop characteristics in the same fiber. The exposure in this case can be accomplished by illuminating the fiber with different wavelengths of light either simultaneously or consecutively. We can accomplish consecutive growths of the single-peaked responses in the same fiber by changing the wavelength of illumination after one portion of the growth has been completed and then re-exposing the fiber. A small change in this wavelength can be obtained with an adjustment of the angle of tilt of the intracavity mode-selecting etalon of the argon laser. Figure 3 shows a filter with a double-peaked response

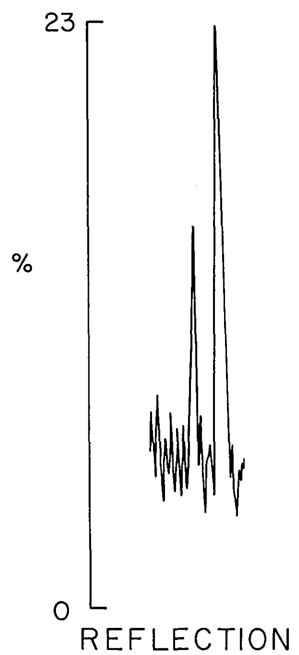

Fig. 3. Reflection spectrum of filter formed by consecutive growth of two single-peak responses. The separation of the peaks is 760 MHz.

produced in this fashion. The separation of the peaks is 7.6×10^2 MHz. This capability of overwriting without erasure of previously written gratings is important in the formation of such devices as comb filters for wavelength-division multiplexed systems. Another method for tailoring the response of the filters is to take advantage of the sensitivity of the growing process to the parameters of either temperature or longitudinal tension. If the fiber is subjected to a temperature gradient along its length during exposure, a monotonically chirped,[3] and therefore broadbanded, grating would result. Furthermore, formation of these filters in multiport devices can theoretically lead to wavelength-selective couplers of high efficiency. Such devices could be made by multibeam exposure of the grating with the illuminating beams entering through separate ports of the device.

In summary, we have demonstrated the formation of very-narrow-band reflection filters in an optical fiber by utilizing the photosensitivity of the fiber core. The filters are characterized as length-limited Bragg filter structures. Desired response characteristics can be obtained through the filters' capability to be overwritten to produce complex responses. These filters are thus promising candidates for use in a variety of devices useful for optical communications.

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Note added in proof: The authors thank the reviewers for pointing out that the maximum reflectivity of the filters may be influenced by dynamic beam-coupling effects, as described by J. J. Amodei and D. L. Staebler, RCA Rev. **33**, 71 (1972).

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