Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication

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(Received 27 December 1977; accepted for publication 10 March 1978)

The observation of photosensitivity in Ge-doped core optical fibers is reported. The photosensitivity is manifested by light-induced refractive-index changes in the core of the waveguide. Narrowband reflectors in a guide structure have been fabricated using this photosensitivity and the resulting DFB reflectors employed as laser mirrors in a cw gas laser in the visible.

PACS numbers: 42.80.Cj, 42.80.Mv, 42.80.Lt, 42.60.Fc

There has been considerable interest recently in the theoretical study[1-5] and fabrication[6,7] of optical waveguide filters for light-wave communications. A major motivation for this work has been the improvement in the data-transmission capacity of light-wave communication links that results from the implementation of wavelength-division-multiplexed (WDM) systems. The waveguide filters can provide the accurate frequency discrimination required to separate the individual channels. Such filters can provide a further improvement of communication channel capacity if they are used as external reflectors to control the oscillation modes of the source. The resulting narrow oscillation linewidths increase the potential channel packing density and reduce the effects of dispersion on each channel in high-capacity WDM single-mode fiber links.

Tailoring of the filter response for specific applications can be accomplished by implementing the appropriate longitudinal aperiodic perturbation of the waveguide structure.[1-4] Experimental work in this area to date has been restricted to the demonstration of simple band-stop filters or linearly chirped filters in planar waveguides.[6,7] These structures have proven difficult to apply in practical form because of both their mode mismatch with optical fibers and their high optical loss. The loss presently limits the effective length of the filter structures fabricated in such waveguides to approximately 1 cm. The complexity of the response characteristic that can be synthesized[1,3,4] is thus similarly limited. Other approaches which can overcome these limitations of planar waveguide filters therefore appear desirable.

We report here the fabrication of tunable high-quality optical-waveguide filters with low scattering loss and the potential for extremely high-frequency selectivity. We form these filters in a low-mode-number silica fiber waveguide by the exposure of the photosensitive core of the fiber to intense contradirectionally propagating coherent beams; these are excited in the fiber with the aid of a single-mode argon-ion laser, operated on either the 488.0- or 514.5-nm line. The standing-wave pattern that results exposes the fiber and forms the periodic perturbation that comprises the filter. This photosensitive phenomenon has not to our knowledge been reported previously and may occur to a greater or lesser extent in fibers other than of the type we have used, Ge-doped silica-core fiber with numerical aperture (NA) in the range 0.1–0.2 and core diameter 2.5 μm. The photosensitivity is greatest for the larger Ge dopant concentration. Filters with effective lengths limited not by fiber loss but by the coherence time of the argon-ion laser (~0.1 μsec) can be fabricated in these fibers.

To test the effectiveness of a number of these fiber reflection filters, we used each of these in place of the output reflector of an argon-ion laser and were able to obtain stable cw oscillation on the 488.0-nm line consistently. This demonstration represents the first reported distributed feedback (DFB) oscillation of a gas laser operating in the visible region of the spectrum.

A schematic of the DFB argon-ion laser, together with the monitoring apparatus, is shown in Fig. 1. It consists of a Spectra-Physics Model 170 laser head with the output reflector removed and a ×32 microscope objective for coupling the beam to the optical waveguide reflection filter. The filter consists of a 1-m strand of Ge-doped-core fused-silica clad fiber with a NA = 0.2 and core diameter ≃ 2.5 μm. To condition the fiber to provide strong back reflection at the 488.0-nm line, it is first exposed for several tens of seconds to coherent contradirectional beams at this wavelength, each typically carrying 250 mW, until a periodic structure is formed in the core; the presence of the periodic structure results in an increase in the back reflection of the fiber to a value many times that of the Fresnel reflection (4%) from the input face of the fiber. Figure 2 shows the growth in reflectivity of one of our fiber strands as a function of exposure time; the transmission of the fiber decreased simultaneously by an order of magnitude at the wavelength used for exposure. The insets in Fig. 2 show typical transmission and reflection spectra of a 62-cm fiber-strand narrowband filter with somewhat lower reflectivity. The filter bandwidth in this case is resolution limited by the fiber length. Techniques for measuring these narrowband reflection filter characteristics will be reported elsewhere.

After the filter-formation process, the device is mounted and aligned to take the place of the argon laser output reflector. With proper alignment of the gain channel and reflection filter, strong lasing is

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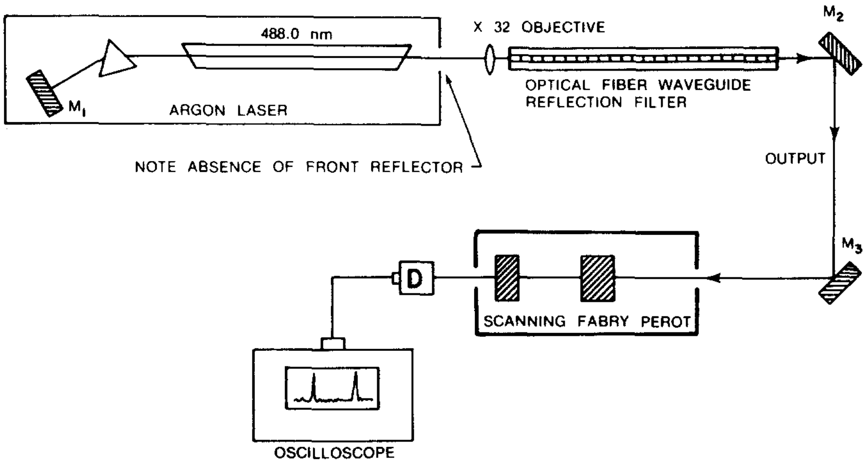

FIG. 1. cw distributed feedback argon-ion laser. The fiber reflection filter (~1 m long) takes the place of the output reflector and gives rise to narrowband oscillation.

observed on the 488.0-nm line. With a properly fabricated filter the output is single mode.

The power supply current at threshold for laser action with the reflection filter forming the cavity is 25 A, which is significantly lower than the 36-A threshold observed with a 4% output reflector (lasing off the fiber end). We note that the back-reflected modes from the waveguide core, after collimation by the ×32 microscope objective, have a diameter approximately 1.5 times the mode diameter of the argon-laser gain channel, decreasing the overlap by ×2.25. The effective reflectivity of the filber in this application is thus about 20% (44%/2.25).

As the DFB argon laser oscillates, the fiber is continually being exposed to the oscillation frequency which has the lowest threshold. The DFB structure for this frequency is thus reinforced and the laser becomes long lived.

Further evidence of the narrowband nature of the filter is obtained when the fiber is excited by the broadband multimode output from an argon-ion laser oscillating at 488.0 nm. With this 5-GHz-wide illumination, the throughput is essentially unchanged from the unexposed fiber condition. The transmission of the reflection filter measured at low power with other wavelengths, e.g., the 514.5-nm line, is similarly not affected by the filter formation process at 488.0 nm. These observations indicate that the periodic perturbation of the waveguide core is due to light-induced refractive-index changes and not to changes in absorption characteristics as would occur, for example, in the formation of color centers.

The filter response is extremely sensitive to the environmental factors present while the filter is in the process of formation, as well as to conditions prevalent during measurement of the response function. In particular, temperature fluctuations and gradients as well as mechanical stress acting on the fiber guide affect the response of the filters dramatically. The equation that describes the temperature and stress dependence of the optical-fiber waveguide-filter response upon which we base our sensitivity figures is

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{n}\left(\frac{\partial n}{\partial T}\right)\Delta T + \frac{1}{d}\left(\frac{\partial d}{\partial T}\right)\Delta T + \left(1+\frac{1}{n}\,\frac{\partial n}{\partial S}\right)\left(\frac{1}{d}\,\frac{\partial d}{\partial F}\right)\Delta F, \quad (1)$$

where the resonance condition is given by $\lambda = 2nd$; $\Delta\lambda/\lambda$ is the normalized resonance shift due to a temperature change ΔT and an applied force ΔF; S is the strain, n is the refractive index; d is the spatial period of the perturbation forming the filter structure. For fused silica, $\partial n/\partial T = -0.6\times10^{-5}/{}^\circ\mathrm{C}$, $(1/d)(\partial d/\partial T) = 0.4\times10^{-6}/{}^\circ\mathrm{C}$, and $(1/n)(\partial n/\partial S) = -0.29$. With these values and the Young's modulus, we obtain

$$\Delta\nu \sim 2.04\Delta T - 20.7\Delta W \quad (2)$$

for the frequency-shift dependence on temperature and loading for our fiber at 488.0 nm, where $\Delta\nu$ is in GHz, ΔT in °C and, ΔW is the load in g. Equation (1) suggests that either temperature gradients or differential loading applied either before or after filter formation will broadband[1] its response function by shifting the resonance condition by different amounts at different points along the length of the filter. This technique may be used to synthesize filters with desired response functions.[1-4]

In summary, we have reported the presence of a photosensitive mechanism in a Ge-doped silica core

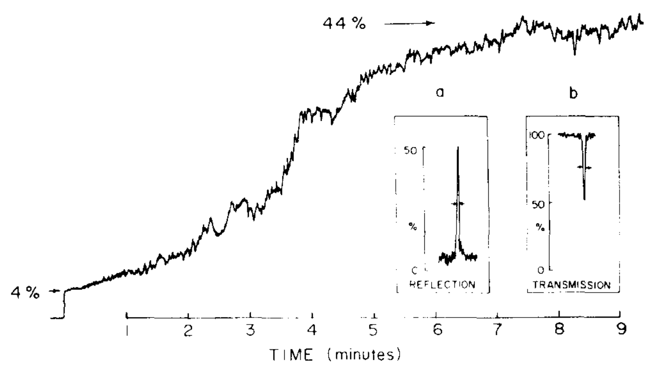

FIG. 2. Build-up in time of the reflectivity of a 1-m strand of Ge-doped core optical fiber (NA = 0.1, core diameter = 2.5 μm). The guide is carrying 1 W of single-mode 488.0-nm light; the filter structure is seeded by the fiber-output-end Fresnel back reflection. Note that the filter reflects the light in the core; therefore, assuming a realistic launch efficiency ≈ 50%, the true reflectivity of this filter is correspondingly 88%. Insets (a) and (b) show respectively typical reflection and transmission spectra of a 62-cm fiber-strand narrowband filter. The indicated full width at half-maximum (FWHM) of both spectra is 200 MHz.

fiber manifested by light-induced refractive-index changes. We have utilized this phenomenon to form high-quality long-length reflection filters in fibers. We have shown that these filters, whose reflectivity can reach nearly 100% of the light launched in the core, can be used as distributed feedback structures to replace the output reflector of an argon-ion laser. The filters have many potential applications, for example, in laser mode control and as synthesized filters with tailored response characteristics for use in high-capacity wavelength-multiplexed light-wave communication systems. As well, the photosensitivity of the fiber guides may find use as a storage mechanism and in wavelength-selective switches and couplers.

The photosensitivity of Ge-doped-core fibers has important implications for the performance of this type of waveguide in a communication system; the dispersion and loss of the guide may be affected in use should the photosensitivity exist in the wavelength regions of interest to optical communications (0.8–0.9, 1.1–1.4 μm). Finally, we note that filters for these spectral regions can be made by difference spatial-frequency techniques using two sources in the visible if adequate photosensitivity is not present in the infrared for direct writing.

The authors are grateful for the technical assistance of R.G. Lamont.

Note added in proof. The maximum reflectivity of an absorption hologram volume recording is approximately 7%, whereas a dielectric hologram volume recording can reach 100% reflectivity. The reflectivities that we observe are therefore not due to an absorption mechanism such as the formation of color centers.

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Lifetime and quenching rate constants for Kr_2F^* and Kr_2^*[a)]

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(Received 13 January 1978; accepted for publication 7 March 1978)

A broadband 2.5-ns-long argon excimer photolytic source was used to initiate the reaction sequence resulting in the formation of Kr_2F^*. The resulting fluorescence signal at 400 nm depended on the radiative and quenching processes of Kr_2^* as well as Kr_2F^*. The radiative lifetime of Kr_2F^* was found to be 181 ± 12 ns. The rate constants for quenching by F_2 and Kr are $4.3\pm0.4\times10^{-10}$ and $<2.0\times10^{-14}$ cm^{3}s^{-1}, respectively. The Kr_2^* coupled l_u, O_u^- lifetime is 280 ± 30 ns and the rate constant for quenching of Kr_2^* by F_2 is $2.1\pm0.2\times10^{-10}$ cm^{3}s^{-1}.

PACS numbers: 33.70.Fd, 31.70.Hq, 82.20.Rp, 31.50.+w

One of the many interesting results to come out of the rare gas–halide kinetics research has been the discovery of the triatomic rare gas–halide excimer. Intense broadband fluorescence from high-pressure e-beam-excited mixtures of Ar, Kr, and F_2 has been seen at 290 nm [1] and 410 nm.[1,2] The pressure dependence of the fluorescence intensity has been the basis for assigning the ionically bonded excimers Ar_2F^* and Kr_2F^*, respectively, as the sources of this broadband emission.

Recent *ab initio* calculations[3] on Ar_2F^* have reinforced the experimental conclusions. It was shown that the lowest-bound excited state of $Ar_2F(2^2B_2)$ in an isosceles triangle configuration (C_{2v} symmetry) can undergo electric dipole allowed transitions to two lower repulsive covalent states (1^2B_2 and 1^2A_1) with a wavelength near 270 nm and a combined lifetime of 128 ns. Similar calculations on Kr_2F^* have substantiated this species as the 400-nm emitter having a lifetime of 132 ± 25 ns.[4]

The experiment reported here is a direct measurement of the Kr_2F^* lifetime. This was accomplished by optically pumping atomic krypton in the presence of F_2 with a broadband 2.5-ns-long argon excimer source near 129 nm. The broadband excitation source pumps the Kr across the entire absorption width. At the pressures used here, this absorption feature is pressure broadened. The detector views the gas at the center of the cell, which achieves its state of excitation (predominantly) by photoabsorption in the wings of the Lorentzian line shape. At the decay times and pressures measured in this experiment, diffusion losses out of the field of view and wall deactivation are negligible.

The prime advantage of this method is that optical pumping at the wavelength and intensity used here produces no charged particles, a complicating feature of electron or proton beam studies.

The excited atomic krypton (Kr^*) thus produced reacts

a)Work done under the auspices of the United States Department of Energy.

