for a longer period of time. We are presently investigating this possibility.

Finally, our cavity has another practical feature. Since the optical length is proportional to the transit time of a photon, any photon which was initially at $x=1+t_0$ will strike the pellet's surface [after reflecting off $\Gamma(t_0)$] at the same time. Thus, if the incident plane wave is pulsed, then $\Gamma(t_0)$ converts this wave into a converging spherical wave with the identical pulse shape.

The author would like to thank Dr. Fred Tappert of the Courant Institute for his reading of this manuscript and Professor J. B. Keller of the Courant Institute for his helpful discussion and suggestions. The results contained in this paper were obtained at the Courant Institute of Mathematical Sciences, New York University, with the National Science Foundation, Grant NSF MCS 7607521.

[1]K. A. Brueckner and S. Jorna, Rev. Mod. Phys. **46**, 325 (1974).
[2]J. Brandstatter, *An Introduction to Rays, Waves, and Radiation in Plasma Media*, 1st ed. (McGraw-Hill, New York, 1963).
[3]K. Lee, D. W. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Fluids **20**, 51 (1977).
[4]J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, Phys. Rev. Lett. **37**, 1052 (1976).
[5]R. K. Luneburg, *Mathematical Theory of Optics*, 1st ed. (University of California Press, Berkeley, 1966).

Broad-band grating filters for thin-film optical waveguides[a)]

C. S. Hong, J. B. Shellan,[b)] A. C. Livanos,[c)] A. Yariv, and A. Katzir[d)]

California Institute of Technology, Pasadena, California 91125
(Received 16 May 1977; accepted for publication 17 June 1977)

Broad-band grating filters have been fabricated on glass thin-film waveguides and evaluated with a tunable dye laser. Measured and calculated filter responses were found to be in good agreement. Grating filters with bandwidths of 300 and 150 Å, and reflectivities of 18 and 40%, respectively, are reported.

PACS numbers: 42.80.Cj, 42.80.Lt, 42.80.Fn, 42.82.+n

Gratings on the surfaces of thin-film optical waveguides have been used in a variety of applications such as couplers,[1] beam splitters,[2] and filters[3,4] in integrated optics. The grating with nonuniform period (chirped grating) has been the subject of current theoretical interest.[5,6] Recently chirped gratings fabricated on thin-film waveguides as output couplers[7] and wavelength demultiplexers[8] have been demonstrated.

In this work we report the use of chirped gratings for the realization of broad-band optical filters in thin-film waveguides. Chirped grating corrugations were fabricated on sputtered glass waveguides using the procedure described in Ref. 7. A tunable dye laser was used to measure the wavelength dependence of the filters' reflectivities. Bandwidths of 300 and 150 Å and reflectivities of 18 and 40%, respectively, were achieved. These values were in agreement with calculations based on measured waveguide and grating parameters.

Consider a thin-film waveguide supporting only the fundamental mode. A surface corrugation grating with a period equal to half the wavelength of the guided mode will cause the normally incident mode to undergo retroreflection.[3] The analysis of this problem uses the coupled-mode theory.[3,9] In a chirped grating whose period Λ varies as

$$2\pi/\Lambda(z)=2\pi/\Lambda(0)-2\gamma z, \quad 0<z<L, \tag{1}$$

the coupled-mode equations become

$$\frac{dA}{dz}-i\delta A=-i\kappa B\exp(i\gamma z^2), \tag{2a}$$

$$\frac{dB}{dz}+i\delta B=i\kappa A\exp(-i\gamma z^2). \tag{2b}$$

A and B are the complex amplitudes of the incident and reflected modes under consideration. κ is the coupling coefficient, which depends on the profile and the depth

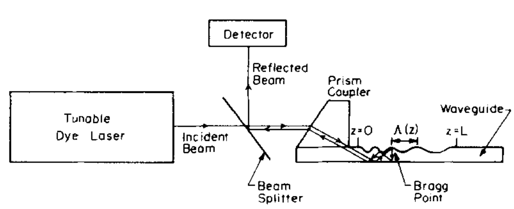

FIG. 1. Schematic of filter evaluation setup.

[a)]Work supported by the National Science Foundation (Optical Communication Program) and the Air Force Office of Scientific Research.
[b)]Fannie and John Hertz Foundation Doctoral Fellow.
[c)]Present address: Hughes Research Laboratories, Malibu, Calif. 90265.
[d)]Present address: Physics Dept., Tel Aviv University, Tel Aviv, Israel.

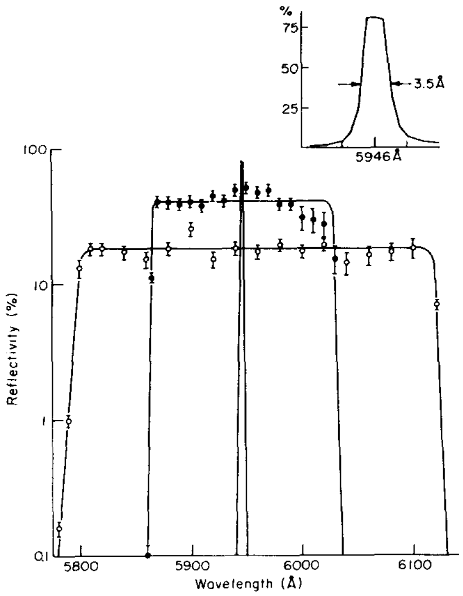

FIG. 2. Reflectivity versus wavelength for three grating filters. ○ represents filter 1; ● represents filter 2. A narrow-band filter (filter 3) is also shown and detailed in the inset.

of the grating corrugation. δ is a phase mismatch factor and is defined by

$$\delta = \pi/\Lambda(0) - \beta, \qquad (3)$$

where β is the propagation constant of the uncorrugated waveguide mode. The point where the Bragg resonance condition $2\pi/\Lambda(z) - 2\beta = 0$ is satisfied shall be referred to as the Bragg point, $z_B = \delta/\gamma$. Equations (2a) and (2b) can be combined to give second-order differential equations for the incident wave A and the reflected wave B. The solutions of these equations are the parabolic cylinder functions.[10] By matching the boundary conditions for A and B and using the asymptotic expansions for the parabolic cylinder functions, we obtain the expression for reflectivity

$$R = 1 - \exp(-\pi\kappa^2/\gamma). \qquad (4)$$

This asymptotic expansion is good for cases when the Bragg point is far from the grating edges, i.e., $5\kappa/\gamma < z_B < L - 5\kappa/\gamma$.[10] However, for large chirps the incident mode is coupled into the reflected mode only over a portion of the grating length, and the resulting reflection may be small. Under these conditions we may set $B=0$ in Eq. (2a), solve for A, and use this approximate solution of A in Eq. (2b) to solve for the reflected wave B. We account for residual waveguide losses by replacing δ everywhere by $\delta + \frac{1}{2}i\alpha$, where α is the (intensity) loss constant.[11] Imposing the boundary condition $B(L) = 0$, the solution of Eq. (2b) using the approximation described above is

$$B(0) = -i\int_0^L \kappa(z)\exp(-i\gamma z^2)\exp[2i(\delta + \tfrac{1}{2}i\alpha)z]\,dz. \qquad (5)$$

Carrying out the integration leads to a reflectivity

$$R = |B(0)|^2 \simeq [\kappa(z_B)^2\pi/\gamma]\exp(-2\alpha z_B) \quad \text{if } 0 < z_B < L$$
$$\simeq 0 \quad \text{otherwise.} \qquad (6)$$

In the experiment a glass waveguide was fabricated by sputter deposition of a layer of Corning 7059 glass on a glass substrate. A Shipley AZ-1350B photoresist film was spin coated on the waveguide. The chirped grating was recorded in the photoresist film by exposing the photoresist film to the pattern produced by the interference of a collimated laser beam and a cylindrically focused beam derived from the same laser.[7] An Ar^+ laser line at 4579 Å was used. The exposure of the photoresist film took place inside a xylene bath, thus reducing the laser vacuum wavelength by 1.51, the index of refraction of xylene. Periods of ~1950 Å were thus obtained. The F number of the cylindrical lens was chosen so that it resulted in a desired period variation over the grating surface whose length was 10 mm. The photoresist grating was then transferred to the waveguide surface by ion-beam etching. To evaluate the chirped grating filters, the output beam from a tunable dye laser (linewidth ~0.5 Å) was launched into the waveguide by a prism coupler. This prism coupler also served as the output coupler for the reflected waveguide mode. The incident and reflected waves were separated by a beam splitter, and their relative power ratio was measured. The experimental setup is sketched in Fig. 1. In a chirped grating different wavelengths are reflected at different points along the grating. The light is launched into the short period end of the grating so as to minimize losses due to coupling into substrate radiation modes. As a result, longer wavelengths penetrate further into the grating and thus undergo a larger attenuation due to the residual waveguide loss. This loss α was determined and the observed reflectivity at λ was multiplied by the factor $\exp[2\alpha z_B(\lambda)]$ to obtain the intrinsic filter reflectivity. The loss-corrected spectral responses for two grating filters with different chirp factors are shown in Fig. 2. Also shown in Fig. 2 for comparison is the response of a uniform-period grating filter (1 mm long) whose band-limited characteristics is presented in the inset. The ability to tailor-design the bandwidth of an optical filter is thus manifest.

TABLE I. Summary of data obtained from three grating filters.

		Period (Λ)	Length (L)	Corrugation depth (h)	Waveguide thickness (t)	Effective index of refraction at λ=5950 Å [a]	Wavelength response	Bandwidth	Reflectivity
Filter 1	Chirped	1905–2005 Å	10 mm	350 Å	0.77 μm	1.524	5810–6110 Å	300 Å	18%
Filter 2	Chirped	1925–1975 Å	10 mm	400 Å	0.85 μm	1.524	5870–6020 Å	150 Å	40%
Filter 3	Uniform period	1955 Å	1 mm	250 Å	0.80 μm	1.519	5946 Å	4 Å	80%

[a] $n_s \sim 1.51$, $n_f \sim 1.54$, $n_a \sim 1$.

The measured parameters of the three filters are summarized in Table I. The bandwidths are in good agreement with the design values, while the measured and calculated values of reflectivity are within 10%.

In conclusion, we have demonstrated the fabrication of chirped grating filters in thin-film optical waveguides. The control of the waveguide, corrugation, and chirp parameters leads to band rejection filters whose response conforms closely to design values.

The authors wish to acknowledge the assistance of D.R. Armstrong.

[1]M.L. Dakss, L. Kuhn, P.F. Heidrich, and B.A. Scott, Appl. Phys. Lett. **16**, 523 (1970).
[2]K.S. Pennington and L. Kuhn, Opt. Commun. **3**, 357 (1971).
[3]H. Stoll and A. Yariv, Opt. Commun. **8**, 5 (1973).
[4]D.C. Flanders, H. Kogelnik, R.V. Schmidt, and C.V. Shank, Appl. Phys. Lett. **24**, 194 (1974).
[5]H. Kogelnik, Bell Syst. Tech. J. **55**, 109 (1976).
[6]M. Matsuhara, K.O. Hill, and A. Watanabe, J. Opt. Soc. Am. **65**, 804 (1975).
[7]A. Katzir, A.C. Livanos, J.B. Shellan, and A. Yariv, IEEE J. Quantum Electron. **QE-13**, 296 (1977).
[8]A.C. Livanos, A. Katzir, A. Yariv, and C.S. Hong, Appl. Phys. Lett. **30**, 519 (1977).
[9]A. Yariv, IEEE J. Quantum Electron. **QE-9**, 919 (1973).
[10]R.B. Smith, J. Opt. Soc. Am. **66**, 882 (1976).
[11]A. Yariv, *Quantum Electronics*, 2nd ed. (Wiley, New York, 1975), p. 526.

Laser-induced resonances in high *n* states of hydrogen-like $^{19}F^{8+}$

J. D. Silver, N. A. Jelley, and L. C. McIntyre[a]

University of Oxford, Nuclear Physics Laboratory, Keble Road, Oxford OX1 3RH, England
(Received 11 March 1977; accepted for publication 1 June 1977)

A laser resonance technique using Doppler tuning has been applied to measure transitions between highly excited states of highly ionized fluorine. Resonance transitions between $n=9$ and $n=10$ levels of $^{19}F^{8+}$ with a mean wavelength of 4796.06 ± 0.24 Å were observed. This wavelength is close to the calculated value of 4796.16 Å for the wavelength of the $9^2L_{17/2}$–$10^2M_{19/2}$ transition.

PACS numbers: 32.30.Jc, 42.60.−v, 07.65.Eh

There have recently been a number of atomic structure measurements for high-Z hydrogenic ions[1–3]; most of them were aimed at a measurement of the theoretically important[4] $2^2S_{1/2}$–$2^2P_{1/2}$ Lamb shift splitting. In such hydrogenic ions the Lamb shifts and fine-structure splittings are also significant in high n states, but do not appear to have yet been studied.

We report here a measurement by a laser resonance technique of the gross structure transition $n=9-n=10$ in $^{19}F^{8+}$. Our result demonstrates that laser resonance methods presently used for high-resolution spectroscopy of neutral and singly ionized atoms both in high-velocity beams,[5] and with more conventional sources,[6] may be applied successfully and with theoretically significant, though somewhat reduced, resolution to the experimentally more difficult case of high n states in very highly ionized fast atomic beams. The experimental method, which uses a high-powered (Doppler tunable) laser, is similar to that employed in a recent experiment[7] designed to measure fine- and hyperfine-structure splittings in the $1s\,2p\,^3P$ state of He-like $^{19}F^{7+}$.

The experiment used intense radiation from an argon-ion laser to induce transitions between states in the $n=9$ and $n=10$ levels of hydrogen-like $^{19}F^{8+}$, produced[8] by passage of a beam of F^{4+} at an energy near 30 MeV through a thin (~10 $\mu g/cm^2$) carbon foil. The fluorine ion beam was produced by the Oxford University tandem Van de Graaff accelerator and beam currents of 2 μA (~8+ charge state) were used. Figure 1 shows the experimental layout. The excited F^{8+} beam passed across the cavity of a commercial 5-W argon-ion laser. Intracavity excitation and ~100% total reflection mirrors at each end of the cavity were used to maximize the laser power available at the beam. By use of a demountable mirror mounted perpendicular to the beam axis in a precision rotating turntable, and with the aid

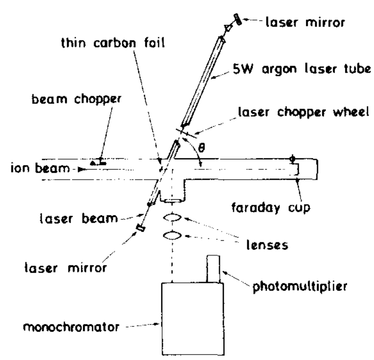

FIG. 1. Experimental layout.

[a]Permanent address: University of Arizona, Tucson, Ariz.