Narrow linewidth excimer laser for inscribing Bragg gratings in optical fibers

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(Received 17 November 1994; accepted for publication 31 January 1995)

A spectrally narrow linewidth KrF excimer laser has been developed for the application of writing Bragg gratings in optical fibers. Two air spaced etalons 80 and 6 cm^{-1} have been incorporated within the laser cavity resulting in a laser line with a linewidth of approximately 4 pm. A stable wavelength setting for writing Bragg gratings has been achieved without the necessity of a feedback mechanism. A study of the formation of Bragg grating in optical fibers with this narrow linewidth KrF excimer laser has been carried out. High quality gratings have been demonstrated in hydrogen sensitized fibers with a pulse energy density as low as 20 mJ/cm^2. Limitations and various problems encountered in inscribing Bragg gratings (such as two simultaneous grating lines) with the narrow linewidth excimer laser source are also discussed. © *1995 American Institute of Physics.*

I. INTRODUCTION

Since the introduction of excimer lasers in 1976,[1] there has been a great deal of interest in narrowing their *spectral* linewidth[2–4] for a number of applications such as photolithography, light-induced detection and ranging, laser-induced fluorescence, *and* stimulated Raman scattering.

Recently, with increasing interest in the fabrication of Bragg gratings in optical waveguides using an interferometric technique, the need for a long coherence length UV laser in the 240–250 nm spectral region is even greater. In particular, the modification of already existing KrF excimer lasers to spectrally narrow linewidth sources is of great interest to many groups working in the field of photosensitivity and fabrication of Bragg gratings in optical waveguides. Spectrally narrow UV sources such as excimer pumped dye lasers which require a doubling crystal to obtain 245 nm are complicated and require frequent changes of dye as well as BBO doubling crystals due to laser-induced damages. On the other hand spectrally narrow linewidth excimer lasers may operate for extended periods of time on the same gas mixture with little changes in their characteristics. However, commercially available narrow linewidth excimer systems are complicated oscillator amplifier configurations which makes them extremely costly. Here we offer a low cost simple technique where any KrF excimer laser may be retrofitted with a *spectral* narrowing system particularly tailored for writing Bragg gratings in a side written interferometric configuration.[5]

In this work, a commercially available KrF excimer laser (Lumonics Ex-600) has been modified to produce a spectrally narrow laser beam. This laser beam was utilized in an interferometric setup to write Bragg gratings in optical fibers to evaluate the performance of this modified excimer laser as the UV source for inscribing gratings in optical waveguides.

II. SPECTRALLY NARROW KrF EXCIMER LASER

KrF (248.5 nm) excimer lasers under normal operation have a very broad spectral profile. For the laser used in this work (Lumonics 600) this was approximately 80 cm^{-1} (0.5 nm). Although the laser wavelength is ideal for photoinducing index of refraction changes in photosensitive fibers, the spectrally broadband operation makes this type of laser impossible to use in an interferometric setup for inscribing Bragg gratings where coherence length is required.

There are a number of techniques for narrowing the linewidth of an excimer laser,[2] including the utilization of diffractive gratings (grazing incidence or Littrow), intracavity prisms, and intracavity etalons. Intracavity etalons were chosen over the other elements due to advantages in efficiency, simplicity, and stability when used in excimer laser oscillators.[4] The system used to spectrally narrow the excimer laser consists of two air spaced etalons mounted at the end of the cavity between a Brewster window attached to the gas chamber and the high reflector (see Fig. 1). In order to maintain one narrow transmission peak within the gain bandwidth of the KrF laser, an etalon with a free spectral range of 80 cm^{-1} and finesse of 16 is used to reduce the transmission bandwidth. A second etalon with a free spectral range of 6 cm^{-1} and finesse of 10 is used to further reduce the spectral linewidth of the laser. Between the Brewster window and the etalon an aperture was inserted to prevent reflections from the highly reflective faces of the etalon feeding back into the gain medium. Even more important, this intracavity aperture *spatially* filters the laser beam resulting in a laser output beam with a nearly Gaussian intensity profile.

The output from the excimer laser with the two intracavity etalons and the aperture was approximately 30 mJ/pulse with repetition rates up to 50 Hz. The pulse width was approximately 12 ns and the lasing wavelength is centered around 248.3 nm with a tunability of 0.5 nm. Although a Brewster window was incorporated at one end of the excimer chamber, due to the short pulse duration there were not enough cavity round trips (less than 2) to selectively polarize the beam in one direction. For our application, where the UV excimer beam is used in an interferometer, *s* polarization (vertical) was necessary for maximum fringe contrast which

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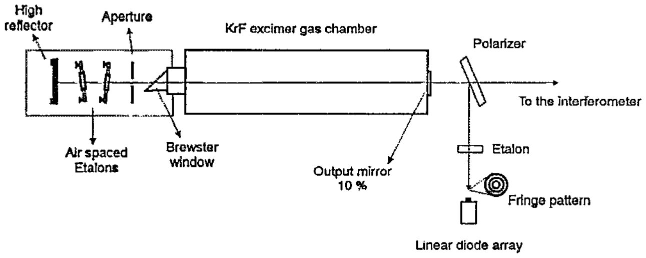
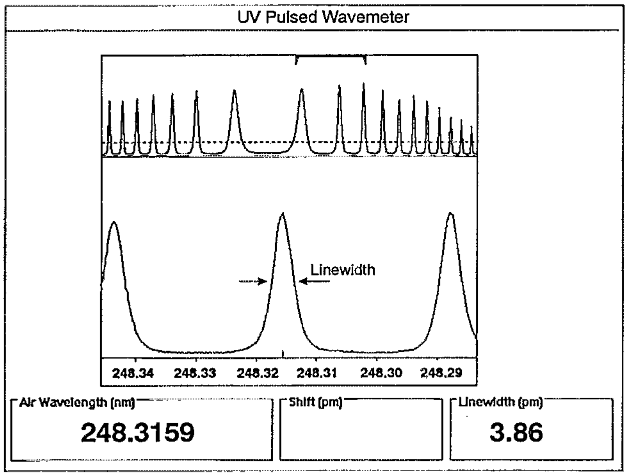


FIG. 1. A schematic of the narrow linewidth excimer laser system. This diagram shows the narrow linewidth unit which consist of two air spaced etalons and an intracavity aperture placed between the KrF excimer gas chamber and the high reflector.

results in better quality Bragg gratings. This requirement made an external polarizer necessary before directing the output laser beam into the interferometer. Part of the output beam was directed through an etalon and the circular interference fringes were monitored with a linear diode array camera to keep track of the laser beam's spectral characteristics. For this study, part of this beam was also directed to a pulsed wavemeter (*Burleigh* UV pulsed wavemeter, model 5500, spectral resolution 0.33 cm^{-1}) to monitor the wavelength and spectral linewidth during Bragg grating formation.



Air Wavelength (nm) 248.3159

Shift (pm)

Linewidth (pm) 3.86

FIG. 2. A typical spectral profile of the narrow linewidth KrF excimer obtained with the UV Burleigh wavemeter (model 5500, resolution 0.33 cm^{-1}).

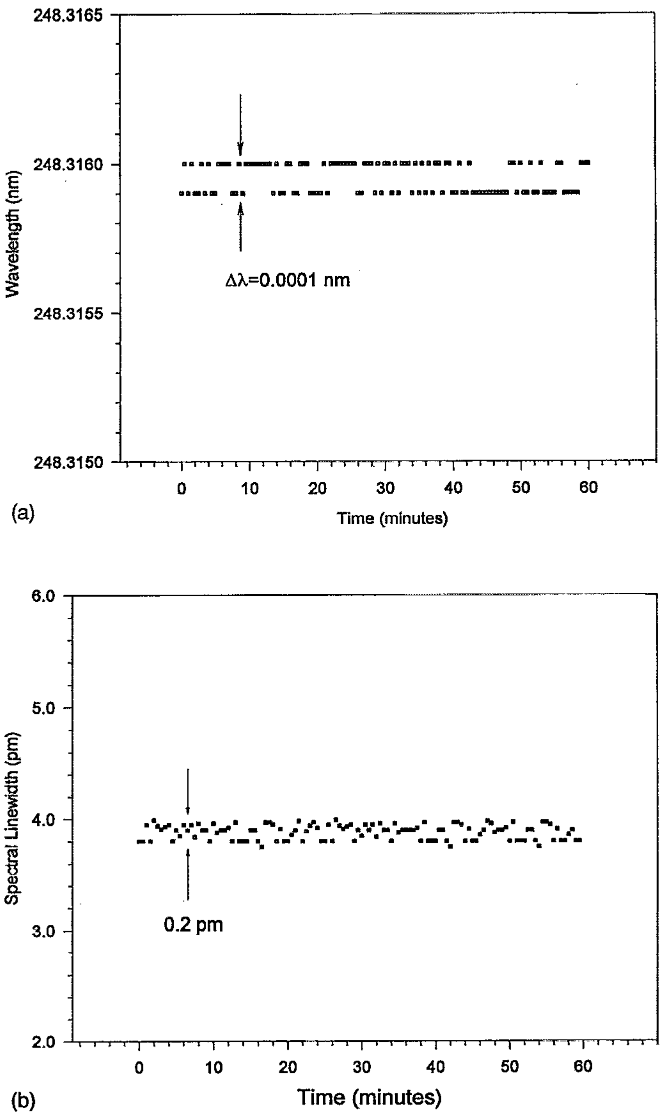


FIG. 3. A plot of wavelength/linewidth stability. (a) In this graph the output laser wavelength of the narrow linewidth excimer laser (after the etalons have been adjusted for optimum operation) is plotted as a function of time over a period of 60 min. (b) A plot of the spectral linewidth as a function of time over a period 60 min.

Figure 2 shows the spectral output from the (spectrally narrow linewidth) SNL-KrF excimer laser obtained with the UV pulsed wavemeter. Figures 3(a) and 3(b) show the temporal behavior of the laser wavelength and spectral linewidth, respectively, over a long period of laser operation at a repetition rate of 10 Hz. In Figs. 3(a) and 3(b) the lasing wavelength and spectral linewidth are plotted as a function of time over a span of 60 min. Clearly, as shown in these graphs, the laser wavelength as well as the laser linewidth remains constant over this extended period of operation. Similar results were also observed over 10 min intervals of the SNL-KrF excimer laser operating at the higher repetition rates of 30 and 50 Hz. The laser seems to remain stable once the two etalons were adjusted for a single wavelength operation. However, since the etalon position (angle adjustment) is strongly dependent on the lasing medium gain spectral profile (for single wavelength operation), any changes in the gain profile will require readjustment of these Fabry–Perot etalons. In particular, changes in the temperature of the gas mixture due to prolonged periods where the system is not in use may change the gain spectral profile enough such that the etalons will need readjustments. Failure to do so might result in the laser operating in two wavelength modes, spaced approximately 80 cm^{-1} apart (due to the coarse etalon) or 6 cm^{-1} apart due to the finer etalon. It will be shown later that multiwavelength operation during Bragg grating inscription will result in more than one grating line or overlapping gratings, depending on the separation of the lasing wavelengths. This suggests that the SNL-KrF excimer laser has to be monitored in order to control and maintain single laser wave-

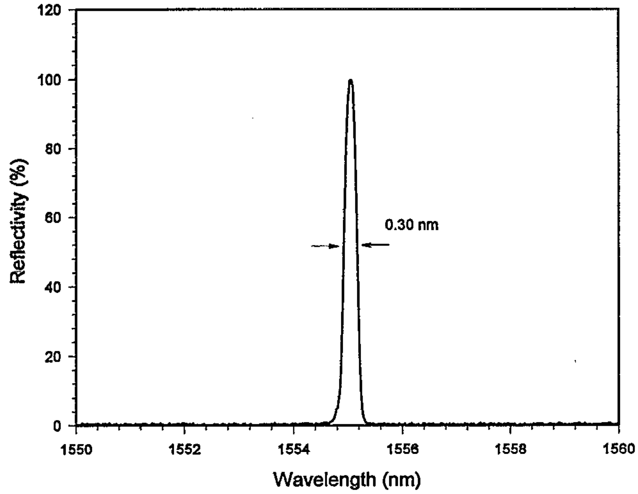


FIG. 4. Reflection spectral profile of a Bragg gratings inscribed in standard telecommunications fiber using the SNL-KrF excimer laser in an interferometric technique.

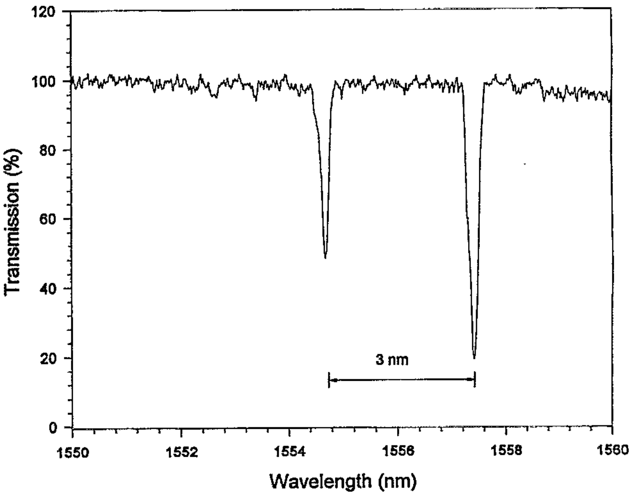


FIG. 5. Transmission spectra of two grating lines inscribed with the SNL-KrF excimer laser operating in two wavelength modes. The separation of the two gratings is approximately 3 nm, which corresponds to two lasing wavelength approximately 80 cm^{-1} apart.

length operation which could be achieved by slight adjustments of the coarse and fine etalons.

III. BRAGG GRATINGS

There are various techniques for writing Bragg gratings[6] which include a phase mask,[7,8] point by point,[9] and the interferometric side written method which is the most versatile.[10] This method allows the inscription of gratings at any desired wavelength by simply adjusting the angle between the two interfering beams. Clearly, such a technique requires a UV source that has a coherence length greater than the length of the desired gratings (at least of the order of 1 cm).

The laser beam from the SNL-KrF excimer laser after passing through a polarizer (see Fig. 1) is directed into the interferometer which is set on a vibration isolated table. The interferometer geometry for this work is described elsewhere.[11] Figure 4 shows a Bragg grating inscribed in normal telecommunications fiber (Philips fiber, 3 mol % Ge) using the SNL-KrF excimer laser after the fiber has been hydrogenated. The hydrogen sensitization of the fiber was necessary to increase the photosensitivity of the fiber. Using the SNL-KrF laser, we were able to achieve very high reflectivities, up to 99%, from the inscribed Bragg gratings in most standard telecommunication fibers which were hydrogen loaded with approximately 0.8 mol % H_2.

In order to understand the various problems encountered in inscribing Bragg gratings using the side written interferometric technique, one has to look at the relation between the UV writing wavelength and the Bragg grating wavelength. This relation is simply given by the following simple expression:

$$\lambda_{\mathrm{Bragg}}=\frac{n\lambda_{\mathrm{UV}}}{\sin\theta},$$

where n is the effective index of refraction of the optical fiber core, λ_{UV} is the wavelength of the UV writing laser source, and θ is the half-angle between the intersecting beams of the interferometer. Clearly, for a fixed intersecting angle, any change in the writing wavelength will result in a direct change in the Bragg wavelength. Thus multiwavelength operation of the excimer laser will cause changes in the Bragg grating spectra profile. As mentioned earlier, the SNL-KrF excimer laser can operate at two wavelengths (when the two etalon are not aligned properly) with a separation of either 80 or 6 cm^{-1} apart. Assuming multiwavelength operation of the excimer laser with the two laser lines being approximately 80 cm^{-1} apart, and using the above equation for calculating the Bragg grating wavelength, it is estimated that the Bragg gratings will have approximately 3 nm separation (for 1550 nm center wavelength). This simu-

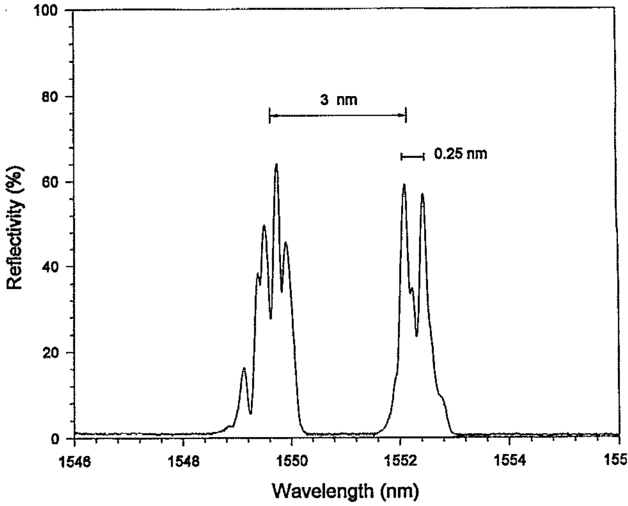


FIG. 6. Reflection spectra of multiple Bragg gratings inscribed with the excimer laser operating in multiple wavelength mode. The 0.25 and 3 nm separations are due to misalignments of the fine and coarse etalons, respectively.

lation is illustrated in Fig. 5 where the transmission spectrum shows two grating lines. Similarly, a two wavelength operation with the two laser lines being only 6 cm^{-1} apart will result in two Bragg gratings 0.25 nm apart. Note that a combination of multiwavelength operation may occur where the UV fringe pattern on the fiber will result in a combination of Bragg gratings as shown in Fig. 6. Although such gratings are within the same physical location which may be useful for some applications, in general this is undesirable. Thus a continuous monitoring of the mode in the laser is essential in controlling the Bragg grating formation.

Stability tests of the excimer laser show that the system may be on for tens of minutes with very little change in the center wavelength and spectral linewidth [see Figs. 3(a) and 3(b)]. A wavelength change of approximately 0.1 pm over the coarse of 60 min operation will result in a Bragg wavelength change of 0.0005 nm (at 1550 nm) which is insignificant since this is much smaller than the linewidth of any grating that can be inscribed in optical fibers.

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