Using microcontact printing to generate amplitude photomasks on the surfaces of optical fibers: A method for producing in-fiber gratings

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This letter describes a method for producing in-fiber gratings that reduces the effects of mechanical and optical instabilities limiting other methods. In this technique, opaque lines formed on the outside of the fiber using a procedure known as microcontact printing, serve as an amplitude photomask for exposure to ultraviolet light. Long-period fiber optic attenuators formed by ths technique demonstrate its advantages. © *1997 American Institute of Physics.* [S0003-6951(97)02001-9]

In-fiber gratings receive increasing attention because of their roles as temperature and strain sensors[1] and their importance as fiber optic mirrors, filters, mode converters, and wavelength demultiplexers.[2] These and other applications motivate the development of reliable and economic schemes for fabricating these gratings. Most methods take advantage of the change in the index of refraction of the core of a fiber produced by exposure to ultraviolet (UV) light.[3] In-fiber gratings formed using crossed UV laser beams were the first to exploit this effect.[4] Although the crossed-beam technique is still used to form Bragg gratings, mechanical and optical instabilities of the apparatus for illuminating the fiber limit the exposure time to several minutes. New techniques using phase or amplitude masks[5–10] relax some of the stability requirements, and sensitization of the fiber to UV light by loading the fiber with hydrogen reduces the exposure time.[11] Even though these methods are useful for forming Bragg and other kinds of in-fiber gratings, for very high performance gratings or for ones that require long exposure times, fabrication schemes that reduce the effects of mechanical and optical instabilities are attractive.

This letter describes a method for generating an amplitude photomask directly on the outside of an optical fiber. Exposure of this printed fiber to UV light produces a grating in the core of the fiber. With this method, the performance characteristics of the grating depend only weakly on the temporal or spatial coherence properties of the source of UV light and mechanical vibrations of the optics that deliver this light to the fiber. We believe that the method will be useful for forming in-fiber gratings with wavelengths longer than $\sim 2\ \mu$m. This letter describes the formation of long-period fiber grating attenuators.[7]

Long-period optical fiber gratings are compact, low insertion-loss in-fiber devices that function as spectrally selective loss elements. These devices[7] have been used as amplified spontaneous emission filters in erbium amplifiers, as band-rejection filters to remove undesirable Stoke's lines in cascaded Raman lasers/amplifiers,[11] and as gain equalizers in multichannel wavelength-division multiplexed systems.[12] These gratings are used for coupling light between two forward-propagating modes in a fiber.[6,13] The periodicities are chosen such that the guided fundamental mode in a single-mode fiber couples out to forward-propagating cladding modes, which, in turn, decay rapidly as they propagate along the fiber axis owing to the lossy cladding-coating interface and bends in the fiber. Since the coupling is wavelength selective, the grating acts as a wavelength-dependent loss element. The wavelength at which the coupling from the guided to cladding modes takes place is dependent on the periodicity, Λ, and is determined by the phase-matching condition, $\beta_{01}-\beta(n)_{cl}=2\pi/\Lambda$, where the β's denote the propagation constants of the respective modes.

Our fabrication method relies on microcontact printing (μCP) to form a photomask bonded to the outside of an optical fiber. μCP uses an elastomeric stamp produced using photolithographic or other means to deliver an "ink" to the surface of a sample. This ink can either prevent the removal or initiate the deposition of material.[14–17] Conformal contact of the elastomeric stamp with the substrate allows the formation of patterns on curved surfaces.[18] Patterns with feature sizes in the micron range can be formed on substrates with radii of curvature as small as 25 microns.[18]

In this work, a polydimethylsiloxane polymer cast onto photolithographically patterned parallel lines of photoresist formed the elastomeric stamp. The stamp was inked with palladium colloids, and an optical fiber stipped of its protective polymeric jacket was rolled over the stamp in a carefully controlled manner (Fig. 1). Contact of the fiber with the raised regions of the stamp transferred colloids to the fiber, and electroless deposition of copper, catalyzed by the palladium, generated a periodic array of opaque copper bands bonded to the outside of the fiber (Fig. 2). With this printing process, we can form arrays of bands with widths as small as one micron over several centimeters of fiber. To produce long-period grating attenuators, the widths of the bands and spaces were between one and three hundred microns.

The copper bands formed a photomask for exposure of the fibers to ultraviolet light (Fig. 3). (The details of the optical apparatus are described elsewhere.)[19] The formation of strongly attenuating gratings in fibers loaded with hydrogen required exposure to UV light for several minutes, while formation of gratings in fibers without hydrogen loading required ten hours. Figure 4 illustrates the results. The gratings formed in hydrogen loaded fibers perform similarly to gratings formed using conventional methods.[7] The good perfor-

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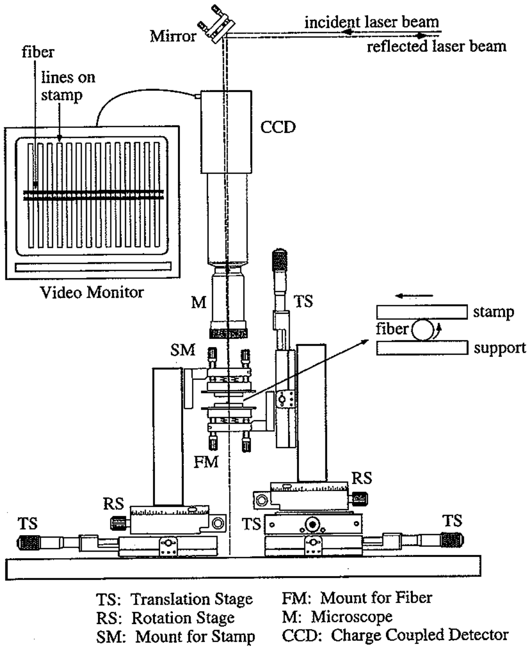

FIG. 1. Apparatus for μCP on optical fibers. Rotation stages allow control of the relative orientation of the fiber and the stamp to within a hundredth of a degree, and translation stages allow control over the stamping time, area, and pressure. Stages with angular adjustments support the stamp and the fiber, and a laser ensures that these stages are properly aligned. A CCD camera connected to a microscope and a video display allows observation of the printing. After proper alignment, the fiber is brought into contact with the stamp and rolled over its surface by translation of the stamp.

mance of the gratings formed in the unloaded fibers (exposure time=10 h) highlights an important advantage of our fabrication scheme: reduction of the effects of optical and mechanical instabilities. With conventional methods, instabilities make the formation of gratings that involve exposure times of this duration difficult.

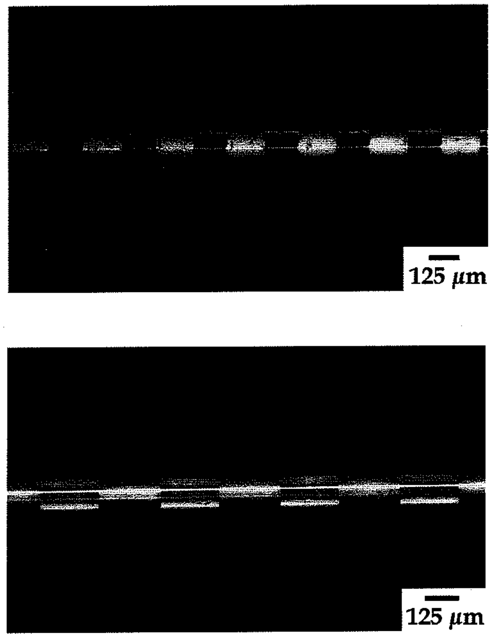

FIG. 2. Copper bands on the outside of optical fibers produced by μCP palladium colloids, followed by electroless deposition of copper. The upper frame illustrates bands with widths of 150 microns, and the lower frame illustrates bands with widths of 250 microns.

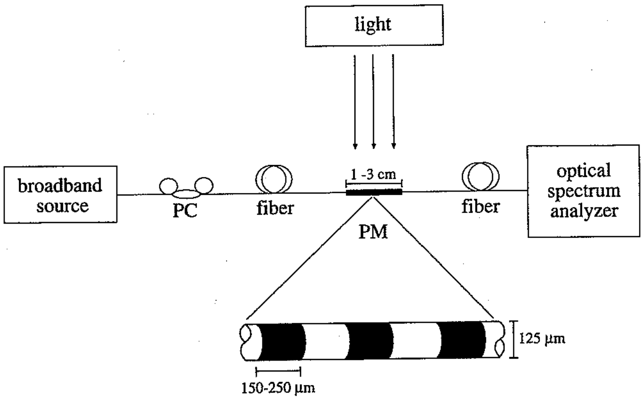

FIG. 3. Apparatus for fabricating in-fiber gratings. Copper bands printed onto the outside of the fibers provided an amplitude photomask for exposure to ultraviolet light. *In situ* measurement of the attenuation of gratings provided a means to monitor the formation of the grating. PC: polarization controller, PM: photomask.

This letter described a technique for the formation of in-fiber gratings that uses an amplitude photomask printed directly onto the fiber. In addition to the long-period fiber gratings illustrated here, this fabrication scheme will be useful for the formation of chirped attenuating gratings as well as other sorts of gratings. We also believe that patterning fibers by μCP will be useful for producing fiber optic devices that involve changes in the index of refraction associated with ion-exchange or elasto-optical effects. These and other possibilities are the subject of current work.

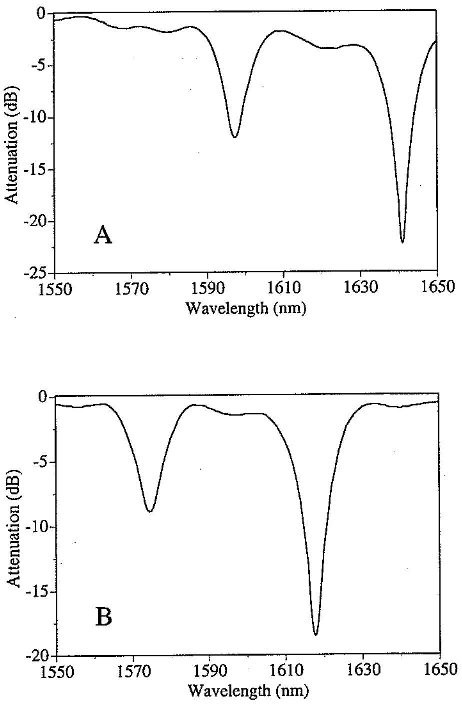

FIG. 4. Attenuation provided by long-period gratings in the cores of optical fibers as a function of optical wavelength. The upper frame shows data from a grating (2.5 cm long, 500 micron period) formed by exposure of a fiber with an amplitude photomask printed on its surface. The formation of this grating required exposure to UV light for ten hours. The lower frame shows data from a similar grating formed in a fiber loaded with hydrogen. The formation of this grating required exposure for seven minutes.

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