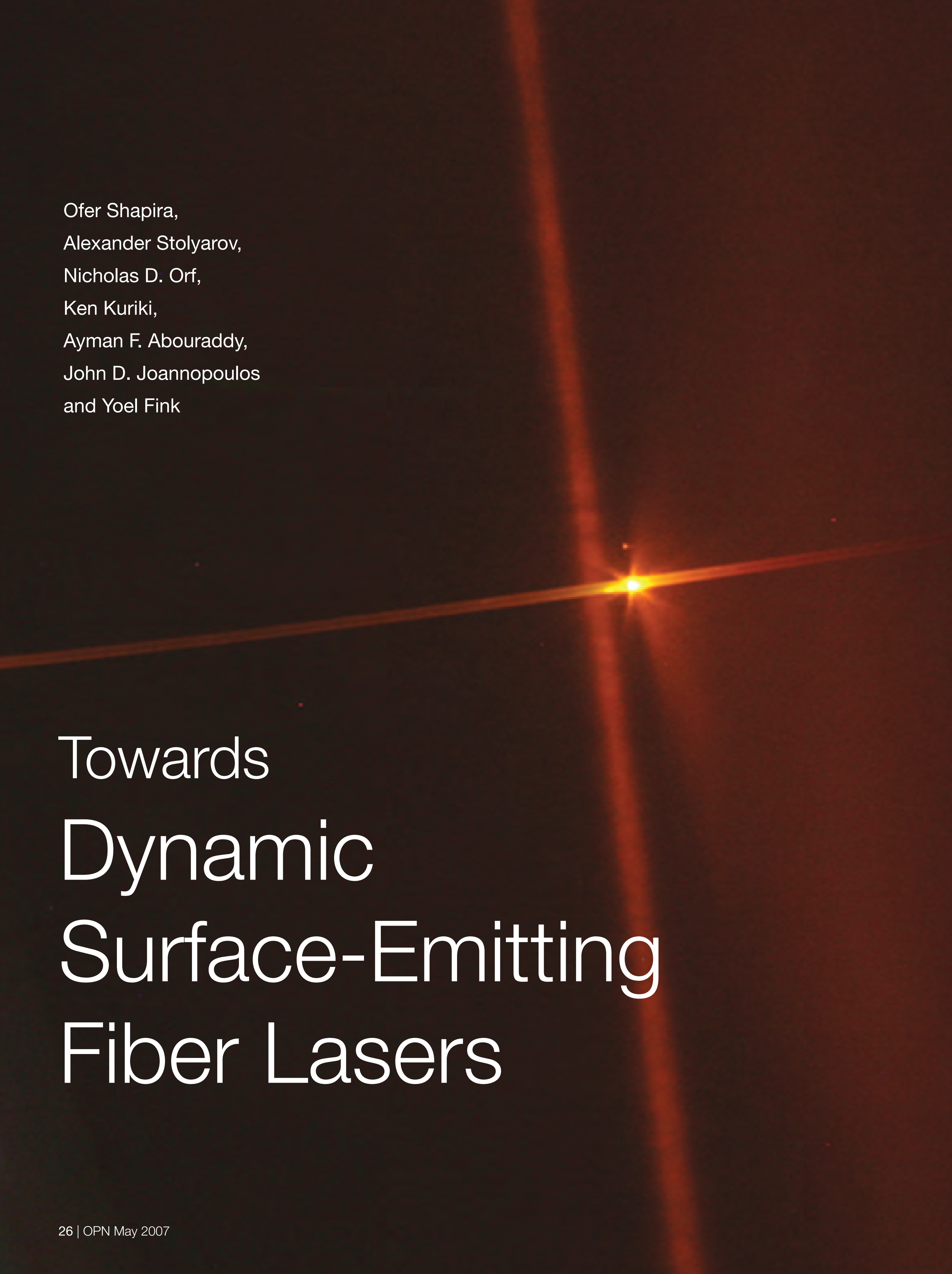

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Towards Dynamic Surface-Emitting Fiber Lasers

The surface-emitting fiber laser combines characteristics of fiber lasers and VCSELs that could be translated into new and exciting applications in medicine, security and “smart” fabrics.

The laser is made of three components—a gain medium, an optical cavity and a pumping process. Since the development of the first laser in 1960, these three elements have come in great variety to address a wide range of needs in science and technology.

Fiber lasers and the vertical-cavity surface-emitting lasers (VCSELs) are two types of lasers that have emerged in the past two decades. They have both been widely used in telecommunication, spectroscopy, medicine and data storage. The surface-emitting fiber laser (SEFL) combines characteristics of both fiber lasers and VCSELs that could be translated into new applications in medical imaging, security and “smart” fabrics. This structure also enables the study of the strong coupling regime in which a high-quality cavity and matter exchange energy repeatedly.

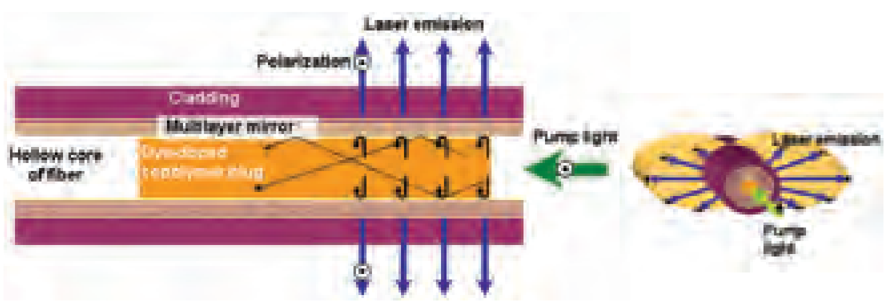
This laser is composed of a hollow core fiber structure, with the gain medium introduced into the hollow core. The walls of the fiber contain a dielectric omnidirectional reflector, consisting of a multilayer structure spanning the entire fiber length. In addition to facilitating guidance of the pump light along the fiber core, this structure provides the optical resonant cavity required for the build-up of laser modes in the radial direction, which results in radiation emission from an extended surface of the fiber.

Until now, emission from fiber lasers originated solely from the fiber ends in the axial direction, with a spot size dictated by the core radius. This is typically achieved by doping glass fibers with rare earth ions such as erbium that serve as a gain medium. The fibers are pumped optically by a co-propagating laser and the resonant cavity is provided by reflectors (e.g., Bragg gratings) located along the fiber axis. These lasers are renowned for their high power, low loss, small emission area, flexibility and simple thermal drawing fabrication process.

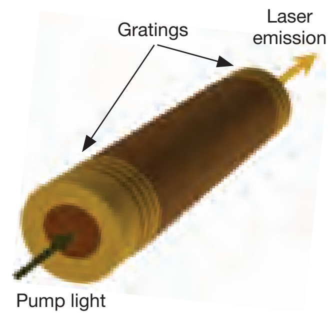
The emission wavelength range of these fiber lasers is limited by the few elements that can produce gain in these structures. SEFLs, on the other hand, have no intrinsic limitation in the range of laser emission. The fabrication process allows for easy control of the dielectric layer thicknesses, which in turn permits tuning the bandgap wavelength of the mirror structure to any desired reflection wavelength. Since the hollow core can host practically any gain medium, laser emission can be obtained by simply overlapping the reflection bandgap of the fiber to the emission spectrum of the gain material. Indeed, we have already demonstrated surface-emitting fiber lasers that lase at nine distinct wavelengths in the visible and near infrared.

The evolution of fiber laser technology from the conventional on-axis emission

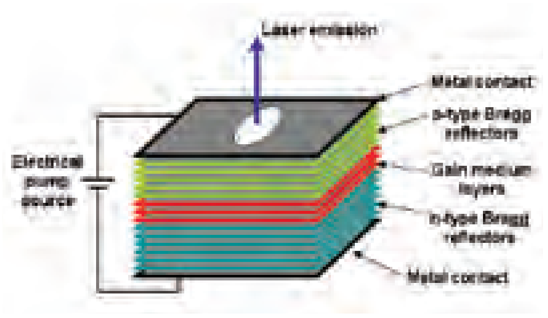
[Surface-emitting fiber]



[Erbium- doped fiber laser]



[Vertical cavity surface emitting laser (VCSEL)]



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to surface emission resembles the evolution of semiconductor-wafer-based laser technology from edge-emitting lasers to the VCSELs. The latter are constructed by sandwiching a light emitting layer between highly reflective mirrors, usually made from dielectric multilayered or epitaxially grown mirrors of distributed Bragg reflectors. Light is emitted perpendicularly from the surface of the mirrors. The SEFL geometry is the cylindrical counterpart of the planar VCSEL, with a cylindrical cavity that is encapsulated by a multilayered dielectric ring that also results in emission through the surface.

The advances in fabrication of semiconductor microcavities and the related VCSELs have led to new means to control the light-matter interaction in solids. In the same manner, SEFLs would enable the study of interaction between matter and cavity modes that exhibit fascinating behavior when the rate in which they exchange energy (the Rabi frequency) is greater than the combined decay rate of the matter polarization and the light in the cavity. When this condition is satisfied, the system is said to operate in the strong coupling regime. The ability of SEFLs to fabricate high quality cavities and introduce a wide variety of matter into the cavities makes them especially good candidates for studying cavity quantum electrodynamics.

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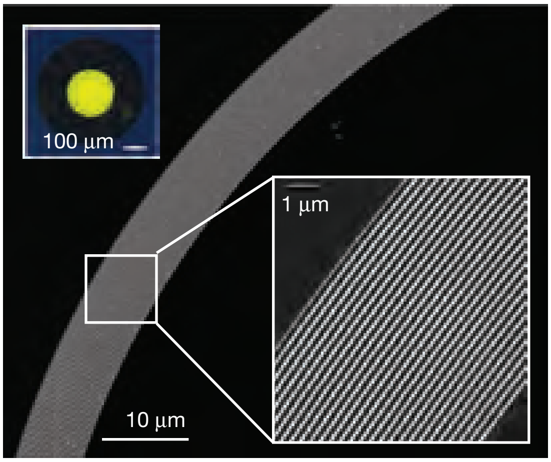
Static surface-emitting fiber lasers

The surface-emitting fiber laser structure comprises a copolymer plug doped with an organic dye gain medium statically situated in the otherwise hollow core of the fiber. The organic dye molecules act as the gain medium for lasing. Surrounding the dye-doped plug is a photonic bandgap (PBG) structure made of 58 layers of a wide mobility gap amorphous semiconductor, As_2S_3, alternating with a high glass-transition temperature polymer, poly(etherimide) (PEI).

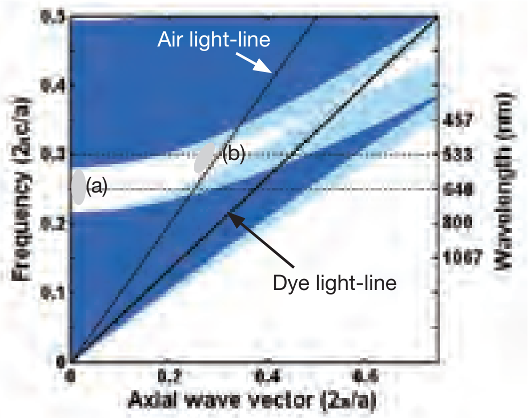
A scanning electron microscope micrograph of the multilayer structure demonstrates the uniformity of the layer thicknesses throughout the fiber. In order to satisfy the quarter-wavelength thickness requirement for a highly reflective dielectric mirror, the individual layer

[SEM micrographs of fiber cross-section of the multilayer mirror structure]



The PEI (black) layers are 89 nm thick and the As_2S_3 (white) layers are 59 nm thick. The top left inset shows a cross-sectional fluorescence micrograph of a Rhodamine 590 doped copolymer plug inside of the fiber.

[Band structure of a multilayer structure]



The multilayer structure consists of alternating layers of PEI and As_2S_3. The white regions represent forbidden (and hence reflected) wavelengths of the structure. The gray oval marked (b) lies along the light line and guides the green pump light along the fiber. The gray oval marked (a) shows wavelengths that are reflected for light incident perpendicular to the structure, corresponding to the radially emitting wavelengths.

thicknesses of As_2S_3 and PEI are fabricated to be 59 nm and 89 nm, respectively, and the structure is terminated by a 29.5-nm thick layer of As_2S_3 to eliminate surface modes.

The gain medium is pumped axially while the resonant cavity provided by the PBG ensures laser emission in the radial direction. The PBG structure performs a dual role enabled by the characteristic shift of the band edges to higher frequencies with increases in wave vector. The normal-incidence bandgap, defined for axial wave vector k = 0 (region a), provides the optical feedback necessary for emitting laser light from the whole surface area in the radial direction. At the same time, the blue-shifted bandgap with axial wave vectors near the light line is responsible for guiding the pump frequency.

We observe broad fluorescence emission from the fiber laser at pump-pulse energies lower than the 86 nJ threshold, while radially directed lasing occurs with sharp peaks at 652 nm above threshold. The figure below shows the emission spectra of the fiber for three different pump energies: below (A), near (B) and above (C) threshold. The lasing threshold occurs at pump energies of 86 nJ and 110 nJ for dye concentrations of 500 ppm and 50 ppm, respectively. The dependence of the emission linewidth and output pulse energy on the pump energy for both 500 ppm and 50 ppm dye concentrations clearly demonstrate laser thresholds. The slope efficiencies are 37.5 percent and 16.5 percent for the 500 ppm and 50 ppm concentrations, respectively.

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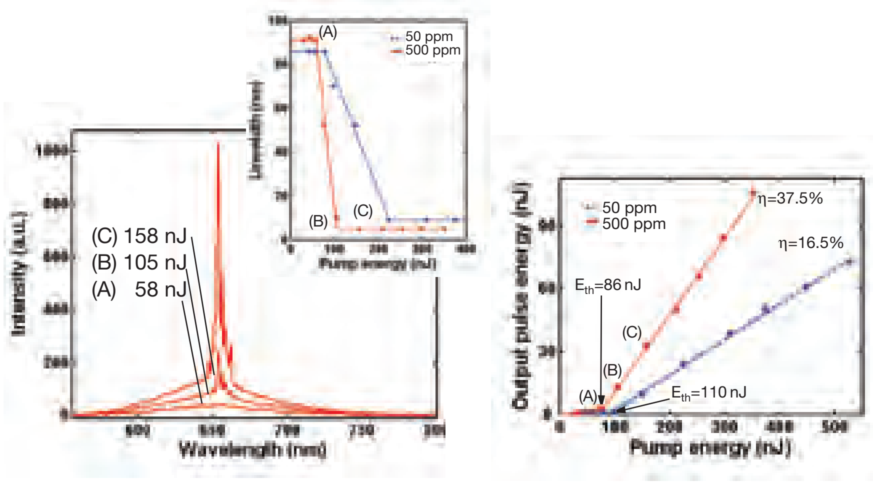
The optical wavefront emanating from the fiber laser has several unique characteristics that stem from the combination of the emission properties of the dye and the resonant cavity design. First, the emitted laser wavefront has a dipole-like radiation pattern. By comparing the radiation pattern to that of a bulk dye-doped copolymer excited with the same pump, we find the dipole-like radiation pattern is not as pronounced as it is in the fiber laser.

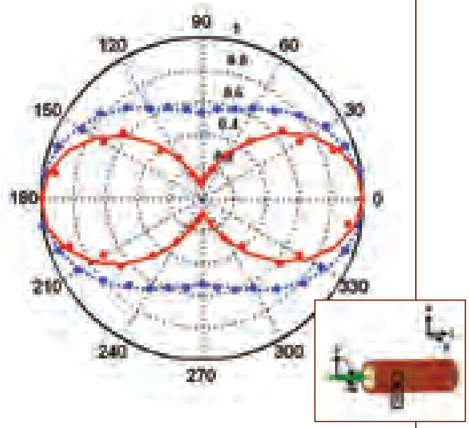
These results can be understood by noting that the polarization of the dye fluorescence is determined mainly by the pump polarization. The polarized dye molecules that are aligned with the pump

[Emission spectra and dependence of laser energy on pump energy]



Left: Emission spectra of a fiber laser below (A), near (B), and above (C) threshold. Inset shows narrowing of the linewidth as threshold is reached. Right: Dependence of the laser energy on pump energy showing threshold values of E_{th}=86 nJ and E_{th}=100 nJ for 500 ppm and 50 ppm dye concentration, respectively.

[Angular intensity pattern]



Angular intensity pattern of the bulk dye (blue) and fiber laser emission (red) at a fixed location along the *y*-axis measured by rotating the input polarization. This measurement is equivalent to fixing the polarization while measuring the emission intensity around the fiber in the *x*-*y* plane.

polarization contribute the most to the fluorescence, resulting in the strongest radiation emitted in the direction orthogonal to the pump polarization.

Since fluorescence polarized parallel to the pump is stronger, cavity modes with this polarization have lower thresholds. Consequently, the fiber laser has an enhanced polarization component parallel to the pump compared to that of the bulk dye emission and a more prominent dipole-like radiation pattern. These interesting results suggest that the direction of the laser beam can be controlled remotely simply by rotating the pump polarization.

A second unique feature of this laser is that emission occurs over a spatially extended region by virtue of the extended surface area of the fiber resonator walls. This is in contrast to planar annular resonators in which the resonator thickness is on the order of the emission wavelength.

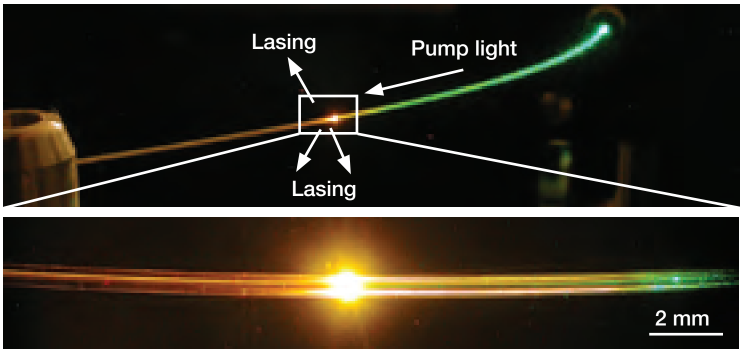
The fiber laser has an enhanced polarization component parallel to the pump compared to that of the bulk dye emission and a more prominent dipole-like radiation pattern. These interesting results suggest that the direction of the laser beam can be controlled remotely just by rotating the pump polarization.

Dynamic surface-emitting fiber lasers

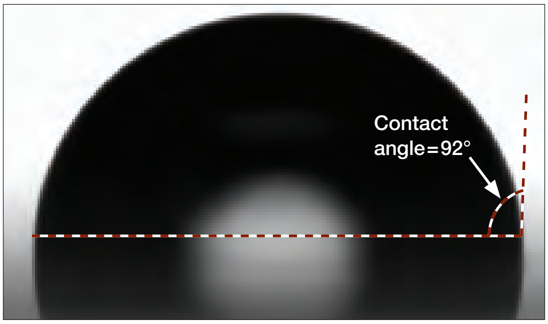
Another key aspect of the SEFL is that the gain medium need not be fixed in place with respect to the fiber. In static SEFLs, the copolymer plug bonds to the inside of the fiber walls as a result of the polymerization process. In these structures, the doped monomer solution is first inserted into the hollow core and subsequently polymerized to prevent it from spreading and wetting the inside surface.

While the polymerization process prevents disintegration of the plug, it forces a constraint on the laser's potential—a static lasing position. Indeed, a static lasing position characterizes all lasers to date. However, with the opportunity to introduce a mobile gain medium into the fiber core, it is possible to engineer an SEFL with a dynamically tunable lasing position.

The physical parameters that need to be considered in creating a dynamic SEFL structure are the surface energies of the host solution and the inside fiber walls. The goal is to introduce a liquid into the core that does not wet the surface, such that it could be transported from one point in the fiber to another without leaving a trail. Water is an ideal



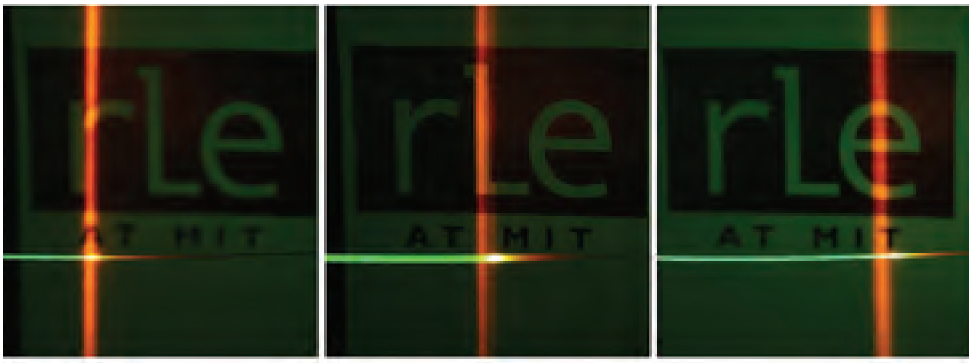
This photograph of the bent fiber demonstrates the hollow-core portion of the fiber that transmits the green pump light, and the dye-doped portion emits orange-colored laser light.



Water droplet on a flat As_2S_3 surface and its reflection. The horizontal dashed line is drawn along the water/substrate interface. The droplet surface intersects the surface at a 92-degree angle.

[Schematic of motion control set-up]

[Dynamic radial lasing]



Dynamic radial lasing is demonstrated as the dye-doped water plug is moved along the hollow core photonic bandgap fiber. The three photos correspond to three different instances in time. The "rLe AT MIT" logo in the background and the fiber are fixed in space, while the microliter water droplet moves along the fiber. The green pump light is seen propagating along the fiber from the left and the orange surface emitting laser light is seen reflecting from the logo in the background, positioned approximately 7 cm behind the fiber.

host fluid due to its high surface tension and large contact angle (greater than 90°) with As_2S_3.

We have designed and built an SEFL that permits real-time control of the fluidic gain medium position within the fiber. Motion control is achieved from one end of the fiber by a series of electronically controlled microdispensing solenoid valves connected to a positive pressure source and a vacuum generator to allow displacement of the dye-doped water plug in both axis directions. The pump beam is coupled to the other end of the fiber, which is open to ambient pressure.

Once one has the ability to position the gain medium at any point along the fiber in real time, the entire surface area of the fiber may be used for lasing. The figure above shows three instances of laser emission from a dynamic SEFL. Note that the fiber is stationary, while the liquid plug has been positioned at three different locations within the fiber. In the figure, laser emission from the dye-doped water plug is seen reflecting from the "rLe AT MIT" logo in the background, positioned 7 cm behind the fiber.

Future applications of SEFLs

Surface-emitting fiber lasers offer unique control over the position, direction and polarization of the lasing wavefront, are inherently wavelength-scalable and can be used for the remote delivery of radial laser emission. They provide the ability to control the gain medium location, spatial extent, and concentration in a mechanically flexible fiber. Thanks to these unique characteristics, these lasers will pave the way for new and exciting applications as well as the enhancement of existing technologies.

In medical imaging, for example, the ability to perform *in vivo* sensing of intact organisms is of great importance. One such technique is fluorescence molecular tomography, in which the emission of near-infrared excited fluorochromes is used to tomographically reconstruct a three-dimensional organism. Another emerging technology is diffusive optical tomography, in which an object is illuminated with an array of sources while an array of detectors measures the light scattered by the object.

A model of the propagation physics is then used to determine the properties of the illuminated tissue. For both techniques, using a denser array of sources can lead to a great improvement in the reconstruction resolution. The SEFL, being a flexible large-area laser that can form any shape and is effectively a large number of point sources, can enhance the capabilities of such imaging techniques.

Recently, side-emitting silica core fibers have received much attention due to potential technologies that might use large area, light-emitting fabrics. Because fibers can be shaped to arbitrary contours, side-emitting fibers may prove to be a particularly useful technology for security systems as infrared perimeters.

SEFLs are well suited for this application because they allow one to have control over the emission direction, which can increase target sensitivity in the effective security zone. In addition, the coherent radiation could be used to detect specific biological or chemical gases, which are traced by specific molecular transitions that match the laser radiation field. ◭

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