Random Laser Action in the Core of a Photonic Crystal Fiber

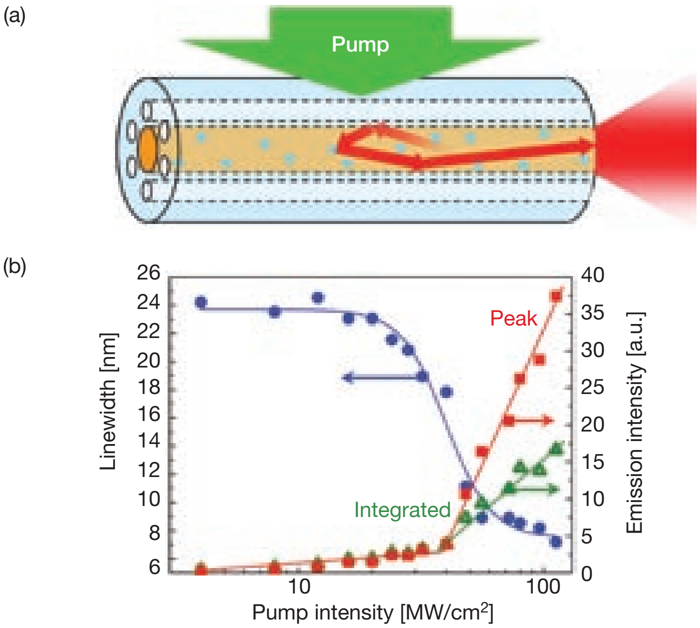
Christiano J.S. de Matos, Leonardo de S. Menezes, Antônio M. Brito-Silva, M.A. Martinez Gámez, Anderson S.L. Gomes and Cid B. de Araújo

A random laser (RL) consists essentially of particles that scatter light and are embedded in a gain medium.[1] After a 1994 study on laser action in a strongly scattering medium,[2] researchers began to study the subject intensively, opening new avenues in strongly scattering gain media. Random lasers have most of the characteristics of conventional lasers: a well-defined threshold, linewidth reduction, a degree of coherence and photon statistics. But they lack directionality.

In order to demonstrate an RL with high degree of directionality, we selectively inserted a suspension of 250 nm rutile (TiO_2) particles in a solution of Rhodamine 6G (Rh6G) in ethylene glycol into the hollow core of a photonic crystal fiber (PCF). We left the cladding microstructure filled with air, generating the first random fiber laser (RFL) and a novel RL geometry, with transverse confinement obtained by total internal reflection and longitudinal feedback provided by scattering.[3]

The PCF had core diameter, cladding pitch and cladding air-filling fraction of about 10.9 µm, 3.8 µm and > 90 percent, respectively. The dye and scatterer concentrations were varied in the range 10^{-5} mol/l $\leq \rho_{dye} \leq 10^{-3}$ mol/l and 10^{7} cm$^{-3} \leq \rho_{scatt} \leq 10^{9}$ cm^{-3}, respectively. For comparison, we also investigated Rh6G solutions without rutile particles.

The main RFL signatures were the threshold behavior, presented by the peak of the laser spectrum, and linewidth reduction. Unlike bulk RLs, the threshold behavior of the RFL also existed for the total (spectrally integrated) emission intensity, which indicates directionality.[3] In the investigated parameter region, one does not observe laser action if there are no scatterers in the Rh6G solution inside the PCF, or if the solution, with scatterers, is in a bulky cuvette.



(a) RFL dynamics. The second harmonic of an Nd:YAG laser laterally excites the PCF (focused by a cylindrical lens). The laser emission exiting the fiber is collected and analyzed in a spectrometer. (b) Emission linewidth (FWHM), peak (squares) and spectrum-integrated (triangles) emission intensities for 10^{-4} M Rh6G solution in ethylene glycol with 10^{8}cm^{-3} rutile particles in the core of the PCF. The solid lines are guides to the eye.

In order to compare various RLs, we introduced a new figure of merit, FOM = $(I_{thr} \times \rho_{dye} \times \rho_{scatt})^{-1}$, which indicates that the RFL is two orders of magnitude more efficient than bulk RLs.[3] We also calculated the β factor for the RFL, obtaining 1.4×10^{-2}, 10 times smaller than typical values for bulk RLs but still significantly higher than those for most conventional lasers.[3]

RLs have been a testbed, both theoretically and experimentally, for several proposed phenomena, such as Anderson localization, the glassy behavior of light and astrophysical lasers, among others. In a recent report, Türeci and co-workers described a unified picture of laser physics to explain the unclear physical mechanisms behind RLs; they substituted the role of the linear cavity resonances in conventional lasers by a novel set of modes called constant flux states in RLs.[4] An adequate theoretical framework for the RFL remains to be developed.

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Toward Roll-to-Roll Production of Polymer Microresonator Lasers

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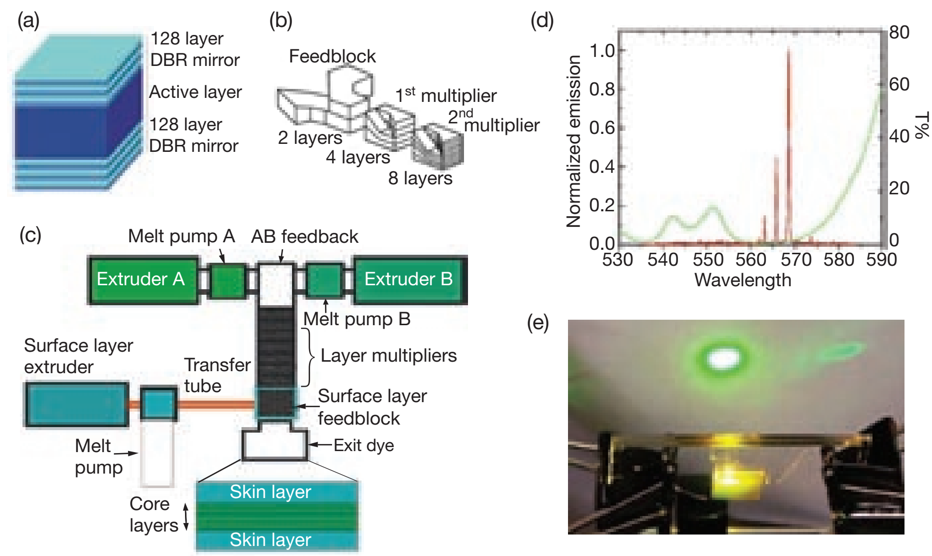
The well-known advantages of polymers for photonic devices are their amenability to low-cost manufacturing and their inherent tailorability. The move toward active polymer photonics such as lasers and nonlinear optical devices, however, requires the presence of active species and complex structures for operation. For example, the manufacture of periodic dielectric media for photonic crystal devices might involve rather complex fabrication steps such as photolithography.

We have taken a significant step toward the realization of both low-cost manufacturing and inherent tailorability by demonstrating the fabrication of high-performance micro-resonator all-polymer lasers using a melt-processing technique amenable to roll-to-roll production. Using the lamination of a dye-infused polymer gain medium with two polymer multilayer reflectors, we have realized low-threshold, high-efficiency surface-emitting distributed-Bragg reflector lasers.[1]

We fabricated the resonator reflectors using a layer-multiplying co-extrusion process; the result was large-area polymer films with 128 alternating polymer layers.[2] Many square meters of highly reflective one-dimensional photonic crystal structures can be fabricated in a few minutes. The extrusion process involves directing melts of poly(methyl methacrylate) (PMMA) and polystyrene (PS) into a two-layer co-extrusion feedblock and then into a series of multiplying elements, each of which divides the melt vertically, spreads it horizontally and recombines it to double the number of layers.

We applied a removable polyethylene skin layer just before the exit dye to create more uniform films and provide protection. Well-defined reflection bands with reflectivities of 95 percent or more arise from the multiplicity of layers and the refractive index differences between alternating PMMA and PS layers. The reflection band can be tuned by the extrusion process design and subsequent stretching. The gain media were fabricated as simple compression-molded thin polymer films doped with laser dyes.



(a) Structure of DBR laser. (b) Layer multiplication scheme and (c) melt-extrusion apparatus with the polymer melts flowing from the extruders, through the feedblocks into the multipliers and then into the exit die. (d) Multimode laser output of an R6G laser superimposed on the transmission spectrum of the distributed Bragg reflector. (e) Bright laser output with residual pump light to the right for an R6G laser.

We used two dyes—rhodamine 6G perchlorate (R6G) and one synthesized by our laboratory 1,4-bis-(α-cyano-4-methoxystyryl)-2,5-dimethoxy-benzene (C1RG).[3] These dyes provide multi-longitudinal mode lasing at about 560 and 510 nm, respectively, with mode spectral widths of about 0.4 nm. Both the longitudinal and transverse modes are well defined.

We fabricated lasers with active layers of various thicknesses. The best performing laser had a 40-µm-thick gain layer containing R6G dye at a concentration of 5.4×10^{-3} M and a threshold fluence of 90 µJ/cm^2. It exhibited a slope efficiency of 19.3 percent. We modeled the lasers as end-pumped 4-level lasers. The minimum threshold occurs when the gain medium optical density is approximately 1.0. This is consistent with our observations from a number of lasers with various gain layer thicknesses and dye concentrations.

In summary, we have demonstrated high performance all-polymer lasers fabricated using a melt processing technique for fabricating distributed Bragg reflector surface-emitting lasers. Our results open the door to the possible fabrication of a variety of active photonic devices.

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Phase-Coherent Injection-Seeded Soft X-ray Lasers at Wavelengths Down to 13.2 nm

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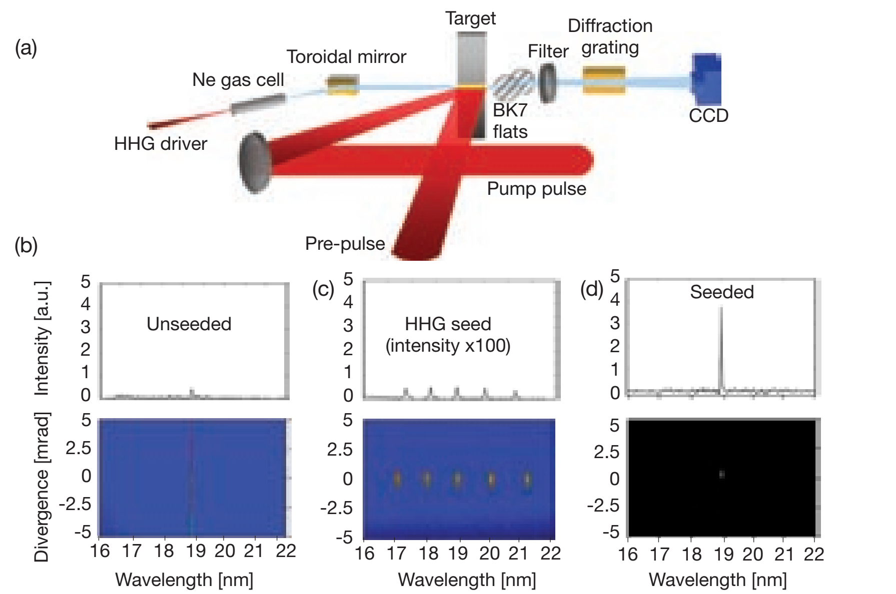
Soft X-ray lasers have been traditionally self-seeded by spontaneous emission. The amplification of random uncorrelated phase wavetrains results in poor temporal coherence. Recent developments include the demonstration of bright table-top lasers operating at a 5-Hz repetition rate in the 13-nm wavelength region.[1] However, these self-seeded lasers have limited coherence. Injection seeding of SXL amplifiers with high harmonics (HH) can generate intense soft X-ray pulses with extremely high coherence, lower divergence, shorter pulsewidth and defined polarization.[2-5]

We have realized the demonstration of SXL with essentially full spatial and temporal coherence operating at wavelengths below 20 nm, and in the technologically important 13-nm spectral region of interest for extreme ultraviolet lithography.[4,5] Gain-saturated laser pulses were produced in dense, laser-created plasmas by amplifying high-harmonic seed pulses in the 18.9-nm, 13.9-nm and 13.2-nm lines of nickel-like Mo, Ag and Cd ions, respectively. These results, obtained using a technique that can also be applied to improve the temporal coherence of free-electron lasers, extend the ability to generate bright phase coherent laser beams to significantly shorter wavelengths.

The HH pulses from a Ti:sapphire laser were injected into SXL plasma amplifiers pumped by intense optical laser pulses impinging at a grazing incidence angle on a solid target. The spectra illustrated the dramatic improvement in laser beam divergence and intensity obtained by seeding a mm-long 13.9-nm nickel-like Ag amplifier with pulses from the 59th harmonic. The beam produced by the unseeded SXL amplifier has a divergence of about 10 mrad. The harmonic seed beam has a much smaller divergence, about 1.2 mrad. Seeding of



(a) The injection-seeded soft X-ray laser. (b) Spectra of unseeded 13.9 nm Ni-like Ag laser. (c) Spectra of HH seed pulse. (d) Spectra of seeded laser. The Ag plasma amplifier was pumped by a 0.9 J short pulse configured into a 4 mm FWHM long line focus.

the SXL amplifier results in a very small divergence, about 0.7 mrad, and a greatly increased intensity. Similar results were obtained seeding the isoelectronic transitions in nickel-like Mo at 18.9-nm and in nickel-like Cd at 13.2-nm.

The spatial coherence of the unseeded and injection-seeded lasers was determined in a Young's double slit interference experiment measuring fringe visibility as a function of slit separation. For the seeded laser, the coherence radius R_c, within which the fringe visibility is larger than 0.61, was measured to be practically equal to the beam diameter, indicative of a very high degree of spatial coherence thorough practically the entire beam. The narrow bandwidth of the amplifier ($\Delta\lambda/\lambda \sim 1 \times 10^{-4}$) greatly limited any frequency chirp, effectively enabling the generation of a pulse with very high temporal coherence, resulting in a phase coherent beam.

These compact SXLs offer new scientific opportunities, such as high-resolution coherent imaging and phase-coherent probing of atomic and molecular systems, in small laboratory environments. ▲

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