Stimulated Emission with Evanescent Gain in the Total Internal Reflection Geometry

J. K. Asane[1], Md G. R. Chowdhury[1], K. M. Khabir[1], V. A. Podolskiy[2], M. A. Noginov[1]*
[1] *Center for Materials Research, Norfolk State University, Norfolk, VA 23504*
[2] *Department of Physics and Applied Physics, UMass Lowell, Lowell, MA 01854-2874*
mnoginov@nsu.edu

Abstract: We demonstrated amplified spontaneous emission (ASE) enabled by evanescent gain at an interface between two adjacent dielectrics. The ASE wave is outcoupled to the high-index medium at the critical angle, enabling observation of spectacular emission rings.

To keep up with the Moore's law [1], future electronics will need nanocircuits operating at the optical frequency [2]. This demand inspires the development of nanocircuit components with gain, such as plasmonic nanolasers and spasers. While plasmonic lasers may have subwavelength dimensions, they suffer from inherent optical loss in metal. Therefore, the development of miniature metal-free lasers with the functionality of plasmonic lasers but without plasmonic absorption would be a major breakthrough in the development of photonic circuitry.

One of the first demonstrated plasmonic lasers was enabled by a surface wave propagating at the boundary between Ag film and dye-doped polymer with optical gain [3]. In the present work, we study (i) whether a guided wave can propagate at the interface between two dielectric layers (one of them with gain) and (ii) whether this mode can support low-loss stimulated emission.

Our samples were polymeric films (PMMA) doped with rhodamine 6G (R6G) dye (gain medium) deposited onto glass substrates (Fig. 1, Panel 1). The film thickness ranged between 1.68 μm and 4.15 μm, and the dye concentrations ranged between c=5 g/l and c=400 g/l (in solid state). At λ=575 nm, (which was close to the wavelength of maximal emission of R6G, λ=563 nm), the refractive indexes of glass and (undoped) PMMA are n_{glass}=1.5239 [4] and n_{PMMA}=1.4912 [5], respectively.

Relevant configurations, in which optical gain was harvested *via* evanescent fields extending to adjacent amplifying low index media were studied by several authors [6-9] and shown to have the total internal reflection exceeding unity, with the maximum at or slightly below the critical angle for total internal reflection (TIR). Using the analytical formula derived in Ref. [10], we have predicted the latter behavior for the parameters of our system.

However, of primary interest to the present study, is not an amplification of the incident light, but rather generation of a guided stimulated emission at the interface between low index R6G:PMMA and high index glass. Lasers and ASE sources harvesting optical gain with evanescent fields have been studied in the literature [6,11,12]. At this time, we report on realization of the miniature source of stimulated emission with evanescent gain, paving the road to micrometer-scale on-chip applications.

The experimental samples were optically pumped at λ=532 nm with the frequency doubled Q-switched Nd:YAG laser, t_{pulse} ~10 ns, at 57 degrees to the sample's normal. The pumped spot was nearly elliptical, with the area equal to ~27 mm^2.The emission was collected at 33 degrees to the sample's normal (Figure 1, Panel 2).

When the sample, R6G:PMMA film (*l*=3.22 μm, *c*=5 g/l) deposited onto 1 mm glass slide, was pumped with low-energy pulses, <0.025 mJ, the emission spectra had maxima at λ=563 nm (Figure 1, Panel 3a), the emission intensities were small (Figure 1, Panel 3b), and the full widths at half maximum (FWHM) ranged between 34 nm and 40 nm (Figure 1, Panel 3c). The corresponding light spots, seen on the samples, are depicted in Figure 1, Panels 3d and 3e. With increase of the pumping energy (0.065 mJ), the bright spot became larger and got surrounded by a diffused light (Figure 1, Panel 3f).

At the further increase of the pumping energy (above the soft threshold at 0.14 mJ), a spectacular bright ring, followed by several other concentric rings (Figure 1, Panels 3g and 3h), appeared on the sample's surface. We numerated these bright rings with integer numbers m=1, 2, 3,…etc. Significantly less intense and often discontinuous emission rings could be seen in between the major "integer" rings; one of them is marked with red arrow in Figure 1, Panel 3h. We numerated the latter low intensity rings as m=1/2, 3/2, 5/2, etc.

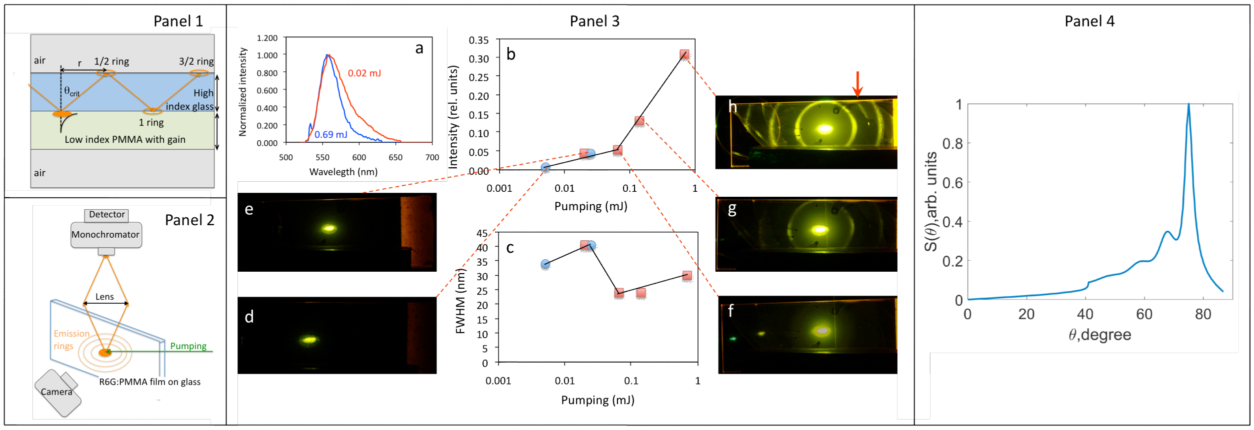

Figure 1. Panel 1: Schematics of the experimental sample; outcoupling and guiding of ASE. Panel 2: Schematics of the experimental setup. Panel 3: Emission spectra of R6G:PMMA (normalized to unity) measured at pumping energy of 0.02 mJ (red trace) and 0.69 mJ (blue trace). (b) Emission intensity plotted against the pumping energy. (c) Full width at half maximum (FWHM) plotted against the pumping energy. (d-h) Photographs of the emission patterns taken at pumping energies equal to 0.0051 mJ, 0.025 mJ, 0.065 mJ, 0.14 mJ, and 0.69 mJ, respectively. Panel 4: Angular profile of emission by a point dipolar source (located within PMMA layer) into the glass substrate.

No rings could be intercepted by a white card placed next to the sample's surface. However, an arched trace of light could be seen on a white card placed above the sample, suggesting that the emitted light was guided by the glass/polymer structure. Therefore, we attribute the rings to the scattering of the otherwise totally internally reflected (TIR) light by imperfect surfaces of glass slides and R6G:PMMA films.

The onset of the emission ring corresponded to a reduction of the emission bandwidth, down to FWHM=24 nm, and an increase of the emission intensity (see Figure 1, Panels 2b and 2c).

Rings radii r are proportional to the ring index m, as well as the thickness of the glass film and are independent of the thickness of PMMA film or pumping intensity (compare Panels 3g and 3h in Figure 1), in agreement with schematics shown in Fig.1, Panel 1. Based on the available data, the angle of emission θ is very close to the critical angle at the glass/PMMA interface, $\theta_c=\arcsin(n_{PMMA}/n_{glass})=78.11^o$.

The experimental observations above are in agreement with theoretical simulations of emission within glass/doped PMMA/air stack that incorporates Green's function formalism (see Ref. [13] for details) and predicts that emission by point dipoles positioned within PMMA film is localized close to TIR angle in the glass substrate (Figure 1, Panel 4). Further analysis suggests that such angular profile is related to the existence of leaky guided mode that is responsible for both angular reshaping of emission and for providing feedback mechanism in for ASE.

The soft ASE threshold is observed in the studied metal-less surface wave geometry at the pumping energy density equal to E_{th}/S=0.24 mJ/cm^2, see Figs. 2b and 2g. According to the conservative estimate (based on the narrowing of the emission band), this value is forty five times smaller than the threshold of stimulated emission of SPP with gain, 10.9 mJ/cm^2 [3]. The reported demonstration of the low-threshold source of stimulated emission "fueled" by harvesting gain in an adjacent micrometer-thick dye-doped medium paves the way to on-chip realizations of low loss all-dielectric lasers with evanescent gain.

This work was supported by NSF grants 1629330, 1830886, 1856515, AFOSR grant FA9550-18-1-0417, and DoD grant W911NF1810472.

[1] G. E. Moore, Electronics, 38, pp. 114-117, (1965).
[2] N. Engheta, Science, 317, pp. 1698-1702 (2007).
[3] M. A. Noginov, et al., Phys. Rev. Lett. 101, 226806 (2008).
[4] R. V. Gibbons and T. J. Ahrens, Journal of Geophysical Research 76, pp. 5489-5498 (1971).
[5] M. N. Polyanskiy, https://refractiveindex.info.
[6] B. Ya Kogan, V. M. Volkov, and S. A. Lebedev, JETP Lett. 16, 100 (1972).
[7] G. N. Romanov and S. S. Shakhidzanov, JETP Lett. 16, 309 (1972).
[8] W. Lukosz and P. P. Herrmann, Opt. Commun. 17, 192 (1976).
[9] P. R. Callary and C. K. Carniglia, J. Opt. Soc. Am. 66, 775 (1976).
[10] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*, Springer, Berlin, Heidelberg (1988).
[11] C. J. Koester, IEEE Journal of Quantum Electronics, QE-2, 580-584 (1966).
[12] Y. Zhang et al., IEEE Photonics Journal, DOI: 10.1109/JPHOT.2019.2907469
[13] L. Nordin, et al., Appl. Phys. Lett. 116, 021102 (2020).