Injection- Seeded Optoplasmonic Amplifier in the Visible

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Abstract: An injection-seeded, WGM resonator-based amplifier has been demonstrated. Synergy between the gain medium, WGM spectrum, and the Raman modes of the amplifier constituents is fundamental. The estimated optical gain is ~ 30 dB.
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An optoplasmonic amplifier, operating in the visible (563 – 675 nm) and injection-seeded by an internally-generated Raman signal, has been realized and will be described. Dye molecules, tethered to the surface of a spherical microresonator by a protein, provide optical gain for the Raman (Stokes) radiation generated within the whispering gallery mode (WGM) resonator, or from another amplifier component (protein, substrate, etc.), by a laser (632.8 or 532 nm) pump source (Fig. 1). Although the gain medium is located external to, and surrounds, the resonator, it lies well within the evanescent optical field of the resonator and, therefore, specific WGMs (Fig. 2) associated with the spherical resonator harvest energy efficiently from the optically-pumped molecules. Because the amplifier gain does not build up from the noise, the coincidence of the Raman "seed" wavelength with a particular resonator mode has the effect of discriminating against all other modes [1, 2]. Energy stored under the amplifier gain profile is extracted predominantly in a single line through injection-locking and power is coupled out of the resonator by a plasmonic array.

To create the optoplasmonic amplifier, photolithography and reactive ion etching process was used. First, the area where nanopillar structures are to be etched is patterned by photolithography. Secondly, by using a mixture of HBr and O_2 gases, the silicon substrate is etched by HBr and oxidized by O_2 simultaneously. The nanocones structures are synthesized by taking advantage of the high etching selectivity of HBr for silicon to silicon oxide (200: 1). Finally, a thin layer of silver coating (80 nm) is applied to complete the fabrication of the plasmonic substrate [3]. Dye molecules conjugated with a protein (NeutrAvidin: NA) are coated onto biotinylated polystyrene microspheres having a nominal diameter, *d*, of 2 μm or 10.1 μm. Tethering of the dye to the surface of the sphere with the biotin-avidin protein positions the molecules 11.1$\pm$0.1 nm from the surface, thereby situating the dye well within the evanescent field of the WGMs associated with power circulating in the spherical microresonator. A single sphere is then placed onto the surface of a plasmonic array structure comprising an 80 nm thick silver film deposited onto an array of Si nanocones. Here, the plasmonic array constitutes an ensemble of nanoantennas that serves as the equivalent of the output coupler common to macroscopic lasers, and facilitates the extraction of optical power from the microresonator atop it.

Irradiating the optoplasmonic structure of Fig. 1 with the focussed beam of a CW He-Ne laser (632.8 nm) results in the PL spectra of Fig. 2 and Fig. 3. Data are presented for nine values of laser power, ranging from 24 nW to 2.0 mW, and with DyLight 650 dye (MW = 1357) tethered to a 10.1 μm diameter polystyrene sphere by biotin-NA. For the lower values of excitation power (P < 1 mW), the WGM structure is clearly present but spectrally-narrow features are also observed, the most intense of which lie at 654.3 and 675.7 nm (Fig. 3). Indeed, as the laser excitation power is increased, the undulations due to the WGMs vanish and the spectra are dominated by these narrow lines. Measurements of the linewidths of these features show them to be below the instrument spectral resolution of 5×10^{-3} nm. Measurements of the variation of the relative intensity at 654 nm with the laser excitation power, summarized in Fig. 4, show a rapid rise in the detected signal for a 10.1 μm diameter sphere and incident powers above 100 μW. The latter corresponds to an optical intensity at the surface of the microsphere of approximately 8 $kWcm^{-2}$.

In summary, owing to the narrow linewidth of the injection seed that is available with Raman scattering and the potential for energy storage in the gain medium surrounding the resonator, the coherence and output power of this visible emitter can be superior to those of existing nano/micro- optical sources. The compound photonic-plasmonic device reported here provides an optical system well-suited for parallel, distributed systems for storing, amplifying and routing optical power.

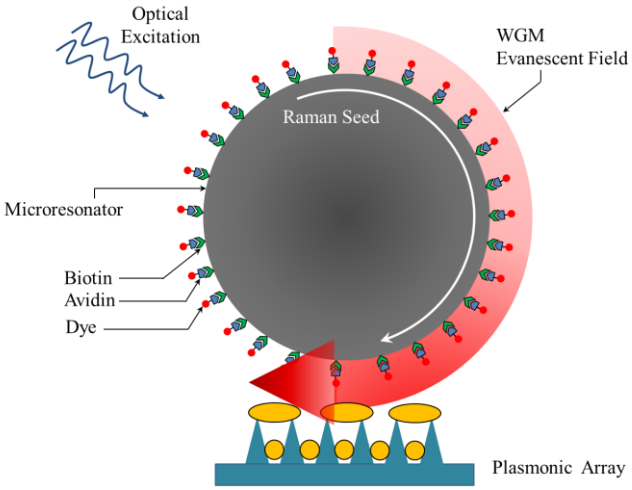

Fig. 1. Schematic of the optoplasmonic amplifier, showing injection seeding of the gain medium.

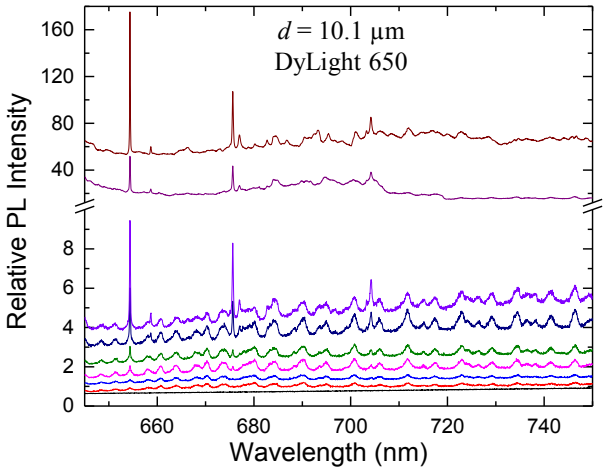

Fig. 2. Photoluminescence (PL) spectra for the optoplasmonic system in the 650-750 nm region. Nine spectral scans, recorded for λ = 632.8 nm pump powers ranging from 24 nW to 2.0 mW, are given.

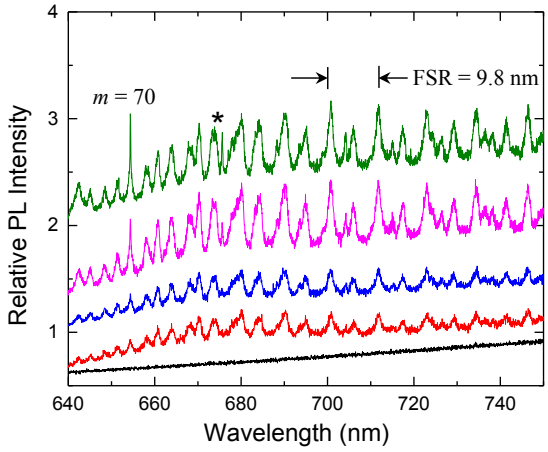

Fig. 3. Magnified view of the five lowest-power spectra from Fig. 2. Note the emergence of the amplified Raman (1st Stokes) line at 654 nm and a weaker feature at 676 nm (denoted by an asterisk).

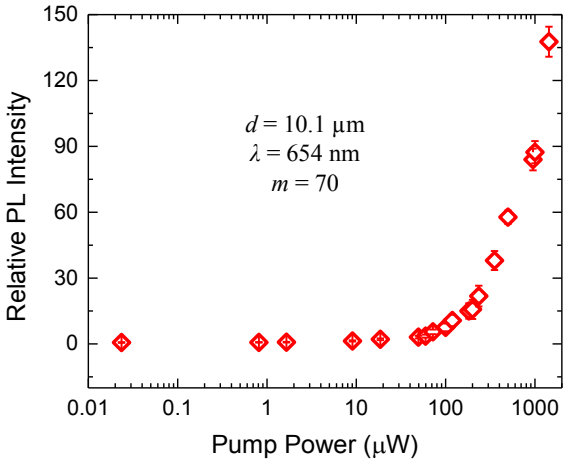

Fig. 4. Variation of the relative intensity of the 654 nm Raman line with the 632.8 nm excitation power for a *d* = 10.1 μm microresonator.

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