A deep-UV plasmonic nanolaser with hyperbolic metamaterials

Kun-Ching Shen, Yuh-Jen Cheng, and Din Ping Tsai

A patterned hyperbolic metamaterial structure excites strong surface plasmon polariton resonance, providing resonant feedback to multiple quantum wells to produce a 289nm UV plasmonic nanolaser.

In recent years, plasmonic nanostructured materials have been used to enhance light emission by creating localized electric fields that confine light fields to regions below the diffraction limit of the material, resulting in efficient light-matter interactions.1 Plasmonic nanolasers based on these materials have been developed by using, for example, a dielectric nanowire or nanorod gain material—the laser amplification medium—placed on a metal film or silica/metal structure to form a Fabry-Pérot cavity resonator (an arrangement of mirrors for multiple light reflection).2, 3 However, the nanowire or nanorod length in these plasmonic nanolasers is often fairly long (several micrometers) and it is not easy to control the nanowire/nanorod orientation, which limits the potential applications of these devices. Here, we discuss our recent work using a metal-dielectric hyperbolic metamaterial (HMM)—a material engineered to exhibit extreme anisotropy upon interaction with light—as a plasmonic cavity to demonstrate a 289nm UV plasmonic nanolaser.

Although the quantum well heterostructures used in these nanolasers, which increase the strength of electro-optical interactions, have a low internal quantum efficiency of 30%, the strong light-matter coupling introduced by the HMM plasmonic cavity can still bring the devices above the lasing threshold. The dispersion relation (the effect of a dispersive medium on the properties of a light wave) of the stacked metal-dielectric HMM is given by:

\[
\frac{k_x^2 + k_y^2}{\varepsilon_\perp} + \frac{k_z^2}{\varepsilon_\parallel} = \left(\frac{\omega}{c}\right)^2
\]

in which \(\varepsilon_\perp\) and \(\varepsilon_\parallel\) are permittivity components perpendicular and parallel to the optical axis \(z\), respectively; \(c\) is the speed of light in a vacuum; \(\omega\) is the angular frequency of light; and \(k_x, k_y,\) and \(k_z\) are wave vectors. When \(\varepsilon_\perp > 0\) and \(\varepsilon_\parallel < 0\), the isofrequency contour for the dispersion relation curve has a hyperbolic form (termed a Type-II HMM), in contrast to circular or elliptical in the isotropic case. Hence, the HMM is expected to sustain a large photonic density of states (PDOS)—available energy levels—resulting from its unbounded isofrequency contour. Indeed, several experiments have been conducted to demonstrate enhanced spontaneous light emission by HMMs through interaction of the large PDOS with the gain medium.4–6 However, only a small portion of most wave vectors towards the \(xy\) plane can excite the Type-II HMM PDOS, a result of the conservation requirements of the wave vector components in the \(xy\) plane, implying the effect of the PDOS contribution is limited.

Figure 1. (a) A schematic representation of a 289nm UV plasmonic nanolaser with a patterned hyperbolic metamaterial (HMM) structure. An aluminum/magnesium fluoride (Al/MgF\(_2\)) HMM multilayer structure is deposited on the UV emitter with a 15nm aluminum gallium nitride cap layer, and a focused 266nm laser source is used to pump the UV emitter. (b) A scanning electron microscopy (SEM) image of the 50×50\(\mu\)m\(^2\) patterned HMM array. The unit cell of the HMM pattern is 400×400nm\(^2\). (c) A magnified cross-sectional SEM image of the HMM pattern showing the thickness of each Al and MgF\(_2\) layer is 20nm. MQW: Multiple quantum well.

Continued on next page
Our approach to increase the PDOS contribution from the HMM is to introduce a patterned HMM structure. Hence, we have designed and fabricated an optimized HMM pattern array—an aluminum/magnesium fluoride (Al/MgF_2) multilayer structure with an aluminum gallium nitride (AlGaN) multiple quantum well (MQW) cap layer—on the device’s UV emitter (see Figure 1). This structure enables the light emission from the quantum wells to indirectly illuminate the sidewalls of the HMM structure (the \(yz\) and \(xz\) planes), and hence these wave vectors can easily satisfy the vector conservation requirements and, therefore, excite more PDOS.

Figure 2. (a) Photoluminescence (PL) spectra of a HMM plasmonic nanolaser at a range of pump intensities. A sharp peak at 289nm with a full-width at half-maximum of \(\sim 1\)nm appears above 100kW/cm^2 pump intensity. Inset: A graph showing the effect of pump intensity on integrated output power. (b) PL spectra of a patterned aluminum control sample. a.u.: Arbitrary units.

We tested the 289nm UV plasmonic nanolaser using a 266nm pumping pulse laser (to transfer energy to the gain medium) and a Horiba T64000 spectrometer to measure the photoluminescence (PL) emission intensity (which was collected at an angle perpendicular to the sample bottom). At low pump intensities (23–53kW/cm^2) the PL spectra show profiles similar to the PL of bare AlGaN MQWs, i.e., the PL intensity peak has a full-width at half-maximum (FWHM) of \(\sim 12\)nm: see Figure 2(a). As the pump intensity is increased beyond 53kW/cm^2, the profiles narrow and become dominant with a sharp peak at a wavelength of 289nm (FWHM \(\sim 1\)nm). In addition, the pump intensity versus integrated output power curve exhibits characteristic threshold behavior with a threshold of 100kW/cm^2: see Figure 2(a) inset. In contrast, over the same range of pump intensities the PL spectra of a patterned aluminum control sample displays regular broad emission without the linewidth narrowing indicative of lasing action: see Figure 2(b).

We used a finite-difference time-domain numerical simulation to study the field distribution of the patterned structure and found that although surface plasmon polaritons (SPPs) are excited in both the Al/MgF_2 and aluminum structures, the Al/MgF_2 HMM structure has many more intricate features. Indeed, SPPs are excited in the parallel Al/MgF_2 interfaces (20nm apart) and the SPPs at each interface, having the same plasmonic resonance, can couple with each other and lead to hybridized SPP coupling. When the incident light induces surface charges on the sidewalls of the HMM structure, SPPs are rapidly generated, propagate along the Al/MgF_2 interface and, as a result of SPP propagation interference, some SPP nodes are formed. The SPP node patterns in different layers are coupled together throughout the whole structure, which generates a strong field within the HMM structure and an intense electric field at the bottom quantum well location (in contrast to that of patterned Al, which is much weaker). This intense localized field in the HMM structure enables strong light-quantum well interactions and, therefore, the lasing action. Hence, our study shows that layered HMM structures greatly enhance light emission when compared with solely metal structures even though SPPs are excited in both cases.

In summary, we have developed a 289nm UV plasmonic nanolaser with a patterned Al/MgF_2 HMM structure on AlGaN MQWs in which, through optimization of the HMM structure, strong SPP resonance can be excited. In addition,
a strong localized field is created at the MQWs, enhancing light-matter interactions. The resonant feedback from the HMM structure to the MQWs enables lasing action, which is not achieved by solely aluminum structures with the same dimensions. This HMM plasmonic structure provides an effective method of enhancing light source emission efficiency and demonstrates the potential for HMM resonators to produce nanolaser devices at subwavelength scales. Our future work in this area will include investigating applications that will benefit from these strong light-matter interactions, such as high-efficiency light-emitting devices, single photon sources, and nanosensing.

Author Information

Kun-Ching Shen, Yuh-Jen Cheng, and Din Ping Tsai
Research Center for Applied Sciences
Academia Sinica
Taipei, Taiwan

References