Nanowire Photonics III: Ring Resonator Nanolasers

Semiconductor nanowires have gained considerable attention recently as components in future integrated optical systems due to their multi-functional behavior as active gain media, passive waveguides, and evanescent-field chemical sensors. As a result of their dimensionality, crystalline structure, and composition, low-dimensional nanomaterials offer a unique platform to study effects such as electron, phonon, and photon confinement as well as mechanical properties. One-dimensional nanostructures made of single-crystalline GaN, including nanowires, nanotubes, and core/sheath structures, already show great promise as nanometer light sources and subwavelength photonic components.

CONSRT researchers, led by Professor Peidong Yang at UC Berkeley, have recently developed a semiconductor gallium nitride (GaN) nanowire-ring resonator laser and demonstrated markedly different lasing properties from the ring structure, compared to its linear counterpart.

The ring cavities were fashioned with a mechanical micromanipulator by pushing two opposite ends of a nanowire together in a side-by-side geometry, ensuring adequate optical coupling (Fig. 1). Wires were manipulated with the probe under a dark-field microscope equipped with a 50x objective (0.55 NA). A HeCd laser provided ~5 mW of unpolarized continuous wave (CW) excitation at 325 nm, while the 4th-harmonic of a Nd:YAG laser (266 nm, 8 ns, 10 Hz) was used for optical pumping.

A crucial physical difference between linear and ring cavity geometries is that the ring resonator case requires phase-matching at the end-facet junction, forcing integer-wavelength boundary conditions for gain within the cavity. The spacing of modes within the cavity, “Δλ”, is given approximately by the well-known expression:

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Δλ = \frac{λ_0^2}{2πR(n - \frac{dn}{dλ} |λ_0|)}
\]

where “λ₀” is the wavelength, “R” is the cavity radius, and “n” is the wavelength-dependent index of refraction. In contrast, linear nanowire lasers act as Fabrey-Perot cavities with boundary conditions that require integer numbers of half-wavelength standing-waves.

There is a clear change in the photoluminescence spectra (PL) of the ring structure as compared to the nanowires, in the emergence of modulation on the red side of the spontaneous emission band (Fig. 2C). Modes do not occur on the blue-side of the PL band because of near-band-edge photon re-absorption. The mode spacing calculated for these peaks (Equation above) correlates well with those expected for a circular resonator: 1.4 nm splitting for an 8 µm ring at 380 nm modal-wavelength, where the measured value (Fig. 2D) is 1.2 nm. Interestingly, the individual modes on the red half of the spontaneous emission band split further into doublets (Δλ ~ 0.5 nm, Fig. 2C, inset).

Due to the dielectric discontinuity after coupling (Fig. 1B), an unavoidable perturbation is introduced within the cavity, breaking the resonance’s degeneracy into clockwise and counterclockwise mode propagation. It is known that a perturbed cavity is theoretically equivalent to two perfect cavities that are coupled, such as with a photonic molecule (see Fig. 1B). This leads to degeneracy splitting into ‘bonding’ and ‘anti-bonding’ modes, using a molecular analogy.

The lasing behavior between nanowires and their resonator counterpart is also markedly different. The emission-maximum of ring laser red-shifts substantially, in some cases by as much as 10 nm relative to the wire (Fig. 2D). For example, under similar power fluences (1050 µJ/cm²), the ring laser in Fig. 2D has its maximum emission intensity red-shifted 9 nm in comparison to the linear structure. By manipulating a linear nanowire into ring geometry, significant changes in nanowire PL, Q-factor, and lasing mode structure can be made.

Our results clearly demonstrated the versatility of nanowire laser cavities for use as tunable laser systems in future integrated-photonic platforms. (For detail, see Phys. Rev. Lett. 96, 143903, 2006)

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