Optical waveguiding along nanometer slits

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Optical field confinement is a topic of immense interest in optical science and technology. Shrinking and confining an optical wave in spatial dimensions not only reduces the size of its footprint, but greatly enhances its field strength in the confined region, leading to stronger light–matter interaction. This is particularly interesting for micro- and nano-photonics where one often likes to have fields confined to less than a wavelength in selected directions. Familiar examples are evanescent fields along optical fibers or waveguides, surface field enhancement of local plasmons, field enhancement on metal tips, and cavity fields in microcavities. A confined light beam with a transverse spot size x times smaller than a wavelength provides the opportunity for conducting near-field microscopy[1] with a resolution x times better than conventional diffraction-limited microscopy.[1]

Generally, confinement of an optical field to the submicron scale is relatively easy, to few tens of nm is more difficult, and to few nm is very challenging.[2–4] The main reason is the difficulty to efficiently couple light into the confined region. Limin Tong and coworkers recently came up with a bright idea to generate guided waves with 1-nm partial confinement.[5,6] They realized that an optical waveguide with a properly designed nm structure in it can have a waveguide mode that has its main profile essentially reproduce that of the mode without the nm structure and a subsidiary nm feature created by the nm structure on top of the main profile. In other words, the new propagating waveguide mode has a nm feature riding along with the broad base part of the waveguide mode. Although the relative energy content in the nm feature is small, the nm confinement can make the energy density in the nm feature extraordinarily high. They constructed such a waveguide by aligning two CdSe crystalline nanorods (of hexagonal cross-section with hexagonal axis along the rods) in parallel with a slit separation of 1 nm between the hexagonal corners of the opposing rods (see Fig. 1). The lowest mode of such a coupled nanorod pair (CNP) waveguide is a TE_0-like mode that has a broad transverse base profile strapping the two nanorods and a nm peak in the middle created by the nm slit. When the CNP was optically pumped above a certain threshold, laser emission in the waveguide mode with a bright central spot from the CNP was observed.[5]

Since the CNP waveguide mode is not very different from those of ordinary optical waveguides except for the nm feature, one would expect that light can be efficiently coupled into the waveguide mode with appropriate impedance matching. Tong and coworkers show in the recent article[6] that by using a tapering optical fiber to transfer light into the CNP along its length (Fig. 2), the transfer efficiency of visible light can be as high as 95% with ~0.2% in the nm peak. The idea can be applied to a wide range of frequencies down to THz. The waveguide mode is not very dispersive, suggesting that the nm field confinement picture should be valid even for femtosecond pulses.

The calculation in Ref. 6 is based on the assumption that wave propagation in the CNP waveguide is linear. This limits the results to cases where energy or power propagating through the waveguide is not very high. If 1 μW of cw power is in the TE_0-like mode of the 1-nm-slit CNP waveguide, the intensity of the nm peak will reach $2 \times 10^9\ \mathrm{W/m^2}$, which is already much too high for nonlinear interaction between the wave and the nanorods to be neglected. The situation is much more serious if light pulses are to be used. Thus, for practical applications, an extension of the calculation to include nonlinear effects on propagation through the CNP waveguide will be needed. It would be interesting if materials, including atoms and molecules, can be incorporated by design into such a waveguide to study their strong interaction with the confined field.

The CNP waveguide is potentially applicable to scanning nanoscopy, but like all near-field microscopic techniques, its resolution depends on how far a sample can be placed away from the end surface of the CNP. The nm-peak of the emitted light from a CNP is expected to spread out in free space very rapidly; a 1-nm emission spot will expand to ~10 nm in a distance of 10 nm from the end surface of the CNP. Development of a scheme to suppress light from the broad base emission that simultaneously impinges on the sample is also needed.

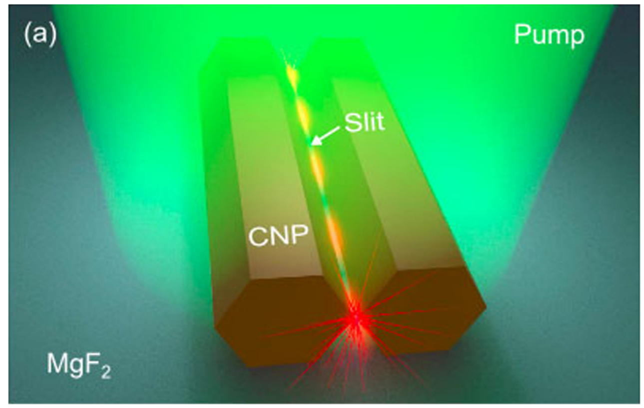

Fig. 1 Schematic illustration of a CNP-based nanolaser with rod diameter of 170 nm and slit width of 1 nm (reproduced from Ref. 5).

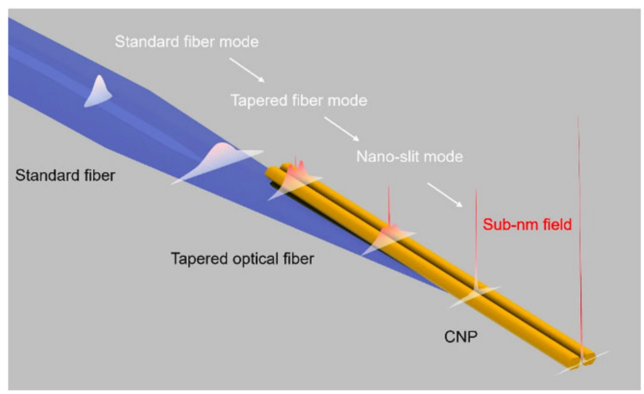

Fig. 2 Schematic of coupling of light from a tapered optical fiber into a CNP waveguide in a distributive way along the length of the waveguide (reproduced from Ref. 6).

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Field confinement in space is analogous to pulse compression in time. Confinement below a wavelength is equivalent to pulse compression to less than a cycle. If partial nm confinement is possible, one may wonder whether, similarly, partial compression of a pulse to a temporal structure much shorter than a period, say, an attosecond spike on a fs pulse, is also achievable. This is probably a far-fetched idea not physically realizable.

References

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