Channel-plasmon nanofocusing

Valentyn S. Volkov, Sergey I. Bozhevolnyi, Jacek Gosciniak, Sergio G. Rodrigo, Luis Martín-Moreno, Francisco J. García-Vidal, Eloïse Devaux, and Thomas W. Ebbesen

Efficient and significant field-intensity enhancement at telecommunications wavelengths using near-field microscopy opens up exciting perspectives for practical applications of nanofocusing.

Recent, rapid developments in plasmonic circuitry suggest numerous possibilities for practical applications of optical phenomena associated with metal nanostructures. Nanoscale field confinement through surface-plasmon (SP) manipulation has great potential to revolutionize many applications in nanophotonics, ranging from quantum optics to imaging, near-field optics, and nanosensing. Various SP-focusing geometries have been suggested to achieve high SP concentrations on scales smaller than the diffraction limit of light (in the surrounding dielectric material). They all support progressively stronger confined SP modes in the limit of infinitely small waveguide cross sections.

The idea of radiation (nano-)focusing (and simultaneously greatly enhancing electromagnetic fields) by gradually decreasing a waveguide cross section is very appealing because of its apparent simplicity. Realization, however, requires the waveguide mode to scale in size along with its cross section, a nontrivial characteristic that is not readily accessible and, for example, cannot be achieved with dielectric waveguides because of the diffraction limit. The physics underlying SP guiding is fundamentally different to and intimately connected with the hybrid nature of SP modes, in which electromagnetic fields in dielectrics are coupled to free-electron oscillations in metals. In the limit of infinitely small waveguides, several SP-guiding configurations exhibit the requisite scale invariance (i.e., the mode size scales linearly with that of the waveguide). The appropriate SP modes are supported, for example, by thin metal films (short-range SPs) and narrow gaps between metal surfaces (gap SPs), and by cylindrical (rod and coaxial) structures. Note that their nanofocusing, although conceptually simple, requires dealing with several complicated issues, such as excitation of the proper SP mode and balancing between SP propagation losses (which increase for smaller waveguide cross sections) and focusing effects.

Several groups have successfully observed plasmon nanofoocusing in various metallic nanostructures. However, these demonstrations have thus far been indirect (based on far-field observations of scattered or frequency-upconverted radiation) and inconclusive regarding the field enhancement achieved. For example, SP modes have been generated on the surface of a gold tapered rod using a grating coupler. Significant dipole radiation from the tip was observed, with the polarization and angular distribution confirming that it was

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generated by the strongly localized, nanofocused transverse magnetic plasmon (polariton). Plasmon nanofocusing in tapered gaps has also been experimentally demonstrated and characterized at a wavelength of 1.53 μm.\textsuperscript{17} In our research, we used a metallic groove with two tapered sections of \textasciitilde 70.6° (the input for direct coupling of the incident light into the groove) and \textasciitilde 17° (the lower output where nanofocusing occurs). Far-field power measurements from each of the output sections allowed us to determine the light intensity (and thus the field enhancement) with a typical local-field enhancement of at least a factor of 10 (enhancement of the electric-field intensity at the narrowest part of the gap).\textsuperscript{17}

We recently suggested another approach (see Figure 1) to realize efficient plasmon nanofocusing with channel-plasmon polaritons (CPPs)\textsuperscript{24} that propagate along triangular grooves of gradually decreasing depth and angle.\textsuperscript{25,26} The gradually increasing CPP-mode localization is equivalent to 2D focusing of the wave and results in significant local-field enhancement along the taper.\textsuperscript{26} The relative simplicity of fabrication allows consideration of more complex nanofocusing structures such as Y splitters, which can provide multiple enhanced outputs: see Figure 2(c) to 2(e).

For experimental verification, we used focused ion-beam milling of a 1.8 μm-thick gold layer (deposited onto a glass substrate coated with indium tin oxide) to fabricate several straight, 150 μm-long V grooves with angles close to 28° and depths of 1.1–1.3 μm that were tapered by gradually decreasing the groove width and/or depth (differently for different structures). We characterized the structures using a collection scanning near-field optical microscope (SNOM)\textsuperscript{27} with an uncoated fiber tip as probe and an arrangement for end-fire coupling of tunable (\(\lambda \approx 1425–1620\) nm) transverse-electric-polarized radiation (with the electric field parallel to the sample’s surface plane) into a groove via a tapered-lensed polarization-maintaining single-mode fiber.\textsuperscript{25} The track of the propagating radiation exhibited, apart from a gradual decay in visibility with propagation distance, a bright spot at its termination: see Figure 1(c).

Following far-field adjustment, we moved the whole fiber-sample arrangement under the SNOM head for near-field mapping of the CPP intensity distribution by the SNOM’s uncoated, sharp fiber tip. We scanned the tip along the sample surface at a constant distance of a few nanometers (maintained by shear-force feedback) and detected the radiation collected by the fiber with a femtowatt indium gallium arsenide photoreceiver. We recorded topographical and near-field optical images of efficient CPP guiding by the V grooves at a distance of \textasciitilde 120 μm from the in-coupling groove edge (to decrease the influence of stray light, i.e., light that was not coupled into the CPP mode) and in the whole range of laser tunability. The optical images are similar to those obtained using photonic-crystal waveguides\textsuperscript{28} with efficient mode confinement (in the lateral cross section) at the grooves and intensity variations in the propagation direction. We thus directly demonstrated efficient CPP nanofocusing, reaching a field-intensity enhancement of up to \textasciitilde 130 times (measured for the amplitude squared with a 2 μm-long taper). Our experimental observations agree with 3D finite-difference time-domain (FDTD) electromagnetic simulations, predicting the possibility of reaching an intensity enhancement of \textasciitilde 1200 and, consequently, opening up exciting perspectives for practical applications of CPP nanofocusing.\textsuperscript{25,26}

In summary, we investigated radiation nanofocusing with CPPs propagating along subwavelength metal grooves that were tapered synchronously in width and/or depth. We directly demonstrated efficient CPPs nanofocusing at telecommunications

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wavelengths using near-field microscopy. Our experimental observations agree with electromagnetic 3D FDTD simulations. Further developments of this concept can be envisaged for other plasmonic waveguides based on gap-SP modes and (with respect to applications for miniature biosensors) by exploiting the exceptional performance of CPP-based nanophotonic circuits (for example, using consecutive Y splitters for multichannel nanofocusing). Thus, we explored the prospect of realizing a multichannel configuration for delivering nanofocused, enhanced CPP fields to several locations using consecutive Y splitters. The level of signal enhancement was fairly constant for the four tapers and consistent with the enhancement observed for the individual 2 μm-long taper—see Figure 2(b)—given the power distribution in the four channels. This experiment demonstrates that our suggested approach for radiation nanofocusing is rather versatile and robust, which is extremely important and indispensable for future applications. Our next step will be to investigate dye-fluorescence enhancement and quenching by single nanoparticles placed at the ends of the tapered gaps.

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Author Information

Valentyn S. Volkov, Sergey I. Bozhevolnyi, and Jacek Gosciński
Institute of Sensors, Signals, and Electrotechnics (SENSE)
University of Southern Denmark
Odense, Denmark

Sergio G. Rodrigo and Luis Martín-Moreno
University of Zaragoza
Zaragoza, Spain

Francisco J. García-Vidal
Autonomous University of Madrid
Madrid, Spain

Eloïse Devaux and Thomas W. Ebbesen
Louis Pasteur University
Strasbourg, France

References

27. DME-DualScope, Herlev, Denmark.