Mode-Matching in 3D Nanophotonic Compressor to Enhance Nanofocusing

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We propose an on-chip nanofocusing structure capable of confining electromagnetic energy within a volume of $3.17 \times 10^5 \lambda^3$ at an enhancement level of $2.2 \times 10^3$ and a nanofocusing efficiency of 80%. The proposed structure can accomplish a Purcell enhancement of $3\times10^3$, and is theoretically predicted to enable the operation of sub-wavelength-scale nano-LEDs and nanodetectors for digital communication over 1 THz (an improvement of about a two orders of magnitude over today's best light-emitting devices).

The proposed structure uses two previously demonstrated devices: (1) the recently demonstrated three-dimensional nanofocusing photon compressor (3D NPC), which consists of a rectangular metal-insulator-metal (MIM) plasmonic nanofocusing waveguide that tapers three-dimensionally into a sub-wavelength-scale tip; and (2) the plasmonic crystal (PLC), which is made of an MIM waveguide with a periodic array of holes oriented perpendicular to the metal layers, similar to photonic crystals, and is used to manipulate the propagation of surface-plasmon polaritons. Because both devices share the same MIM configuration, a PLC can be seamlessly connected to the input (larger) end of a 3D NPC to form a single unit. And, joining two of these units at the sub-wavelength-scale tips forms the proposed structure.

We investigated a silver-silicon-silver (Ag-Si-Ag) MIM configuration on a fused silica substrate for the 1.55-\(\mu\)m telecommunication wavelength. The PLC allows us to tune the coupling rate between the sub-20nm tip and 200nm body of the 3D NPC and to minimize modal reflections. This greatly improves the efficient nanofocusing capability of the 3D NPC. We first investigate the band structure of the PLC and confirm the presence of the band gap around 1.55 \(\mu\)m. By carefully adjusting design parameters such as the number and radius of the PLC holes and the distance between the taper and the PLC holes, we accomplish correct phase compensations at the designed resonance wavelength and optimize the coupling efficiency. Thus, we achieve a modal reflection of less than 1% at resonance ($\lambda = 1.55 \mu$m), and the corresponding reflectance extinction ratio between on- and off-resonance frequencies is larger than 100. The effective nanocavity formed in the structure has a $Q \sim 50$. The difference in the field intensity enhancement between on- and off-resonance wavelengths is a factor of about 100. In the absence
of PLC, we observe broadband transmission in the proposed structure, which agrees with our previous findings for the 3D NPC.

In our presentation, we will discuss detailed simulation results of the proposed structure; simulation techniques; applications of the proposed structure to various nanophotonics implementations including nano-LEDs and/or nano-detectors; and expected performance improvements.