Optical coupling between resonant dielectric nanoparticles and dielectric waveguides probed by third harmonic generation microscopy

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Abstract. We report on the observation of optical coupling between a Mie-resonant subwavelength silicon nanodisk and a silicon waveguide, revealed through third harmonic generation microscopy. Changing the gap between the nanodisk and the waveguide, we observe third harmonic intensity modulation of up to 4.5. We attribute this strong modulation to modifications of the magnetic dipole resonance and local electric fields inside the nanodisk, as supported by full-wave simulations.

1. Introduction
Nanoparticles have important significance for nanophotonics as they possess the strong resonances in the visible and near-infrared spectral ranges. Recently, subwavelength all-dielectric Mie-resonant nanoparticles have been proposed as a promising analogue of plasmonic nanoparticles due to high refractive indices, low Ohmic losses and CMOS-compatible materials [1]. These features make them perfect candidates for integrated photonic devices, such as waveguides and nanoantennas. Moreover, the excitation of strong magnetic dipole (MD) resonance leads to significant enhancement of local electric field inside all-dielectric nanoparticles that enhances nonlinear-optical effects like third-harmonic generation (THG) [4].

Among the studies on single-particle scattering [2, 3], there are a plenty of works devoted to optical coupling between dielectric nanoparticles formations in dimers [5] and high-order oligomers [6]. However, the investigations of optical coupling between all-dielectric Mie-resonant nanoparticles and elements of integrated nanophotonics is lacking. In this contribution, we observe optical coupling between single subwavelength silicon nanoparticles and a silicon waveguide by studying THG as a function of distance between them.

2. Result and discussion
2.1. Sample design
We fabricated samples of “silicon nanodisk—waveguide” pairs out of a silicon-on-insulator wafer with the top silicon and buried SiO₂ layers thicknesses of 280 nm both. The width of waveguide

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was chosen to be 435 nm. The pairs have two varied parameters: the nanodisk diameter and the gap between the nanodisks and waveguides. The diameters of nanodisks were chosen to be 380, 430 and 480 nm, and the distances between nanodisks and waveguides were 105, 185 and 320 nm.

2.2. Experimental method

To probe optical coupling between nanodisks and waveguide, THG microscopy was realized using a confocal laser scanning microscope (CLSM) complemented by a femtosecond Er\(^{3+}\) fiber laser with a pulse duration of 120 fs, a repetition rate of 70 MHz, a central wavelength of laser spectrum of 1545 nm and a width of 40 nm. The “silicon nanodisk—waveguide” pairs were illuminated by the laser pulses tightly focused to a waist of 3 \(\mu\)m in diameter, with the electric component of the incoming field orthogonal to the waveguides. The scattered third harmonic signal was collected by a CLSM objective and was detected by a CLSM photomultiplier.

The most significant THG enhancement, with respect to the THG from the silicon substrate, was observed for nanodisks with diameters of 480 nm, for which its MD resonance lied at the central wavelength of the pump radiation, 1545 nm. The maximum enhancement of THG signal is up to 26. Moreover, THG signal is highly sensitive to the distance between the nanodisk and the waveguide, leading to a significant modulation of THG signal by up to 4.5 in the case of the gap size changing from 185 to 105 nm (blue circles in Fig.1(a)).

![Graph](image_url)

**Figure 1.** (a) Experimental THG enhancement from resonant \((D = 480 \text{ nm})\) nanodisks as a function of the gap between the nanodisk and the waveguide (blue squares) and normalized local electric fields, given by Eq.(1) (connected red squares). The inset shows a scanning electron micrograph of the sample with parameters \(D = 515 \text{ nm}\) and \(L = 165 \text{ nm}\). The scale bar is 200 nm. (b) MD resonance parameters as a function of gap \(L\), with its central position plotted in blue, and full width at half maximum plotted in black. The dashed line is the same as the red curve from panel (a).

2.3. Numerical calculations

In order to study how the waveguide affects the local fields within the nanodisk, electric field strength distribution \(\mathbf{E}(\mathbf{r})\) was calculated and following quantity was plotted in Fig.1(a):

\[
I_{\text{avg}} = \int_{\text{disk}} |\mathbf{E}(\mathbf{r})|^6 dV. \tag{1}
\]
Together with our experimental observations, this non-monotonic distance dependence means that the non-resonant waveguide can enhance field localization in nanodisk and constructively amend its THG signal. To explain this dependence, we calculated full-width at half-maximum (FWHM) and the central wavelength (plotted in Fig.1(b)) of the MD resonance of nanodisk. The maximum of local electric fields (dashed red line) is achieved at the minimum of FWHM of 125 nm at the gap $\approx 200$ nm. At the same time, the minimum of local electric fields is achieved at the maximum of FWHM of 175 nm at the gap $\approx 600$ nm. It may be concluded that the main contribution to the alternating local fields of the nanodisk is provided by the dependence of the MD resonance radiative decay constant. Together with the dependence of FWHM and the central wavelength of MD resonance on the gap, the measured third harmonic represents a manifestation of optical coupling between the nanodisk and the waveguide.

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