Towards Single Antenna On-Chip Surface Enhanced Raman Spectroscopy: Arch Dipole Antenna

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Plasmonic antennas have recently been combined to nanophotonic silicon nitride (SiN) waveguides for demonstrating all-on-chip Surface Enhanced Raman Spectroscopy (SERS). This achievement relied on bowtie antennas engineered to maximize the generated Raman signal. Here, we present numerical investigation of an arch dipole (AD) antenna identically patterned on a rib waveguide and compare it to the best engineered bowtie antenna. Our study shows a 23 fold improvement over the state of the art thus promising shorter integration time and high Signal-to-Noise Ratio which should ultimately enable the detection of on-chip SERS signals originating from a single antenna.

Plasmonic nanostructures have attracted a lot of attention in recent years because of their remarkable ability to enhance dipole excitation and emission near their hotspots. To avoid large and expensive free same optics for excitation and collection of the Raman signal, a great deal of research is going on to integrate plasmonic nanostructures with other nano/micro technologies [1,2]. Recently [3], our group demonstrated indeed that bowtie plasmonic antennas could couple efficiently to a silicon nitride waveguide so that the Raman spectrum of a thin layer of 4-Nitrothiophenol (NTP) was recorded by excitation and collection within the nanophotonic chip. For an antenna gap of 48 nm, pump to Stokes signal conversion efficiency (η) was reported as 2.19×10^{-15}. This means that for 1W pump power, 2.19 fW Stokes power from NTP molecules will couple back into the waveguide. Due to the relatively low efficiency, long integration time and several antennas were required to detect weak Raman signal. Arch dipole (AD) antennas on other hand were shown to exhibit higher SERS enhancements as compared to more simple antennas [4]. In this work, we numerically analyze the same arch dipole (AD) antennas integrated on a single mode SiN rib waveguide and shows that they provide 23 times higher conversion efficiency as compared to the recently published bowtie for the same gap dimension. An enhancement by this factor reduces the integration time and the required number of antennas to just one.

The schematic of the AD is shown in Fig.1. In this work numerical simulations are performed with Lumerical FDTD Solutions. We consider a SiN rib waveguide with refractive index of 1.89 at 785 nm wavelength and a geometry of 700×220 nm^2 supporting a single TE mode. The waveguide is surrounded by a bottom silica cladding, a top air cladding and the AD antenna. A 1 nm thin NTP layer with refractive index of 3 is also defined at the surface of AD [3] and constitutes the Raman medium under investigation. The figure of merit (FOM) for on-chip SERS which incorporates pump to Stokes conversion efficiency as well as the extinction induced by the antenna at pump and Stokes wavelength is defined [3] as $FOM = \eta \times e_s^{1-N} \times (1-t^N)/(1-t)$, where $t = e_s/e_p$, N is number of antennas, e_s and e_p are linear extinctions at λ_s and λ_p respectively. The FOM reaches a maximum at an optimum number of antennas $N_{opt} = log(log(e_s)/log(e_p))/log(e_s/e_p)$.

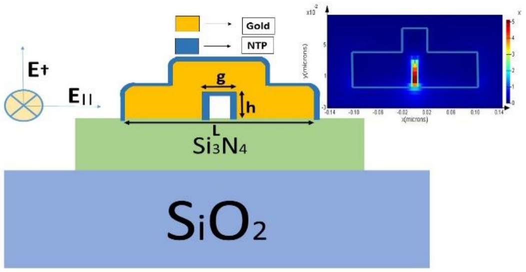

Fig. 1. Schematic of AD antenna on a SiN waveguide. The inset shows the field distribution in the arch.

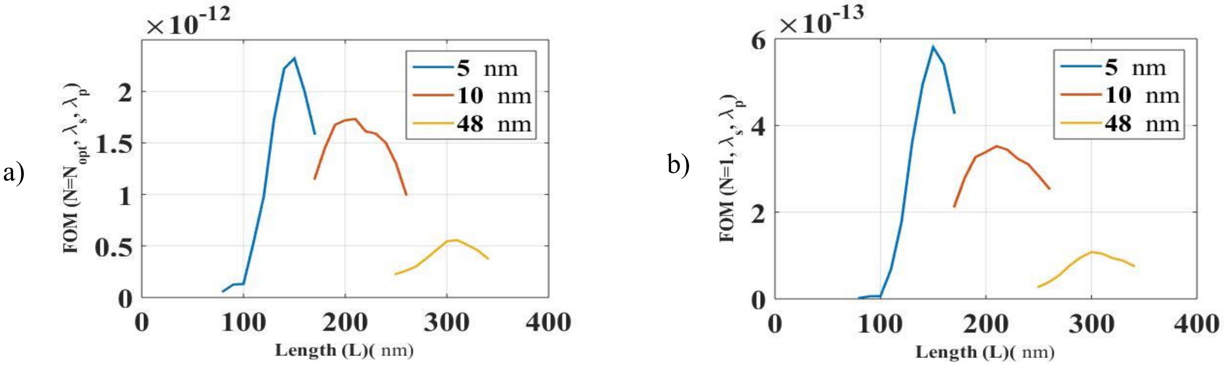

Fig. 2. FOM for on-chip AD antennas as a function of length for an arch height h=30 nm, longitudinal width=30nm (along the propagation direction) and gap of 48 nm. (a) FOM evaluated at N_{opt} and (b) N=1

The *FOM* evaluated at N_{opt}, for an AD antenna for different gaps and lengths is shown in Fig. 2(a). The *FOM* for smaller gaps changes abruptly with length owing to the large plasmon resonance sensitivity to length variations. Increasing the gap from 5 nm to 48 nm reduces the *FOM* just by a factor of 4. This is attributed to the fact that the *FOM* incorporates an average Raman enhancement which is less sensitive to the antenna gap.

For an on-chip BT antenna with 48 nm gap coated with a 1nm NTP layer and with 2 nm Ti adhesive layer, a single antenna conversion efficiency (η_{BT}) of 2.19×10^{-15} is reported in [3]. By using same simulation parameters, it has been noticed that η_{BT} for a bowtie antenna (gap=48 nm) without Ti layer improves by a factor of 2.2 i.e. $\eta_{BT} = 4.82 \times10^{-15}$. A single antenna conversion efficiency for AD antennas is shown in Fig. 2(b). Hence, for a gap of 48 nm without Ti layer, $\eta_{AD} \approx 23\times\eta_{BT}$. The increased enhancement is attributed to the dense population of charges along the side walls which is expected to lead to a better localization of the electric field inside the nano-arch. An enhancement by this factor should capacitate low integration time, high Signal-to-Noise Ratio and eventually enable detection of SERS signals using single antenna.

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