Optical nanoantenna input impedance

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Supporting Information

S.1 Equation for measurement data fitting

The magnitude of electric field along the transmission line represents a standing wave, which results from the optical wave coupling into the coplanar strip (CPS) from the dipole antenna end and the load antenna end. This superposition was described by a geometric-series expansion to account for all the reflections at the impedance mismatched loads:

$$e_0 = e^{(-(\alpha+i\beta)L)}, \tag{S1}$$

$$e_1 = e^{(-(\alpha+i\beta)(L-x))}, \tag{S2}$$

$$e_2 = e^{(-(\alpha+i\beta)x)}, \tag{S3}$$

$$E_Z(x) = E_d\left(e_0 e_1 \Gamma_L + \frac{(e_0^3)(\Gamma_L^2)\Gamma_d e_1}{(1-(e_0^2)\Gamma_d\Gamma_L)} + e_2 + \frac{(e_0^2)\Gamma_L\Gamma_d e_2}{(1-(e_0^2)\Gamma_d\Gamma_L)}\right) + E_L\left(e_1 + \frac{(e_0^2)\Gamma_d\Gamma_L e_1}{(1-(e_0^2)\Gamma_d\Gamma_L)} + e_0 e_2 \Gamma_d + \frac{(e_0^3)\Gamma_L(\Gamma_d^2)e_2}{(1-(e_0^2)\Gamma_d\Gamma_L)}\right) \tag{S4}$$

where Γ_L is the reflection coefficient at the load terminal (for example: a folded dipole), and Γ_d is the reflection at the single dipole terminal. Γ_d is determined in two ways; 1) using a lumped-port excitation, and 2) by fitting the standing wave on a CPS loaded with identical dipoles on either end, with good agreement and with values validated against prior results in reference [25]. E_d and E_L are the magnitude at dipole side and load side. L is the length of the transmission line. The origin is at the dipole end (x=0) similar to the paper. The attenuation constant α was extracted from the decaying complex field amplitude as a function of position along an electrically long CPS predicted through full-wave analysis and the phase constant β was determined from the spatial periodicity in the wave function, respectively:

$$\beta = \frac{2\pi}{\lambda} \tag{S5}$$

$$\alpha = \frac{20\log_{10}(E1/E2)}{8.69d} \tag{S6}$$

where d is the distance between E1 and E2. The attenuation and phase constant should be averaged by calculating through the whole length of CPS.

The impedance of the antenna under test (AUT) was determined from the reflection coefficient, Γ_L, expressed as:

$$Z_L = (\frac{1+\Gamma_L}{1-\Gamma_L})Z_0 \tag{S7}$$

where Z_0 is the characteristic impedance of the CPS, Γ_L is the reflection coefficient at the load terminal which was determined from the fitting equation (S4) and Z_L is the impedance of the load antenna.

The characteristic impedance of CPS, which exhibits a high confinement associated with transmission mode here, was determined by changing the open-circuit and short-circuit load with expression:

$$Z_{in} = Z_o(\frac{Z_L\cosh(\gamma L)+Z_0\sinh(\gamma L)}{Z_0\cosh(\gamma L)+Z_L\sinh(\gamma L)}) \tag{S8}$$

where L is the length of CPS, γ=α+jβ, Z_L is load impedance and Z_0 is input impedance of CPS. In the open-circuit mode operation, Z_L goes to a very large number, $Z_{oc} = Z_o(\frac{\cosh(\gamma L)}{\sinh(\gamma L)})$, while in the short-circuit mode operation, Z_L equals zero, $Z_{sc} = Z_o(\frac{\sinh(\gamma L)}{\cosh(\gamma L)})$. The input impedance of CPS can be achieved from following:

$$Z_0 = \sqrt{(Z_{sc}Z_{oc})} \tag{S9}$$

where Z_{sc} is the input impedance when Z_L is a short-circuit load and Z_{oc} is the input impedance when Z_L is an open-circuit load.

S.2 Numerical method of driven model in HFSS

Ansys high frequency structural simulator (HFSS) is a commercial finite element method solver for electromagnetic structures (http://www.ansys.com). The driven model in HFSS was implemented to compute the input impedance of nanoantennas directly, by driving the nanoantenna at its feed gap with an optical source. Antenna impedance, $Z_{A,}$ can be defined as the ratio of the effective voltage across the antenna arms and the optical displacement current flowing through the gap. Fig. S1 gives an example of feed-gap excitation for the folded dipole antenna in HFSS.

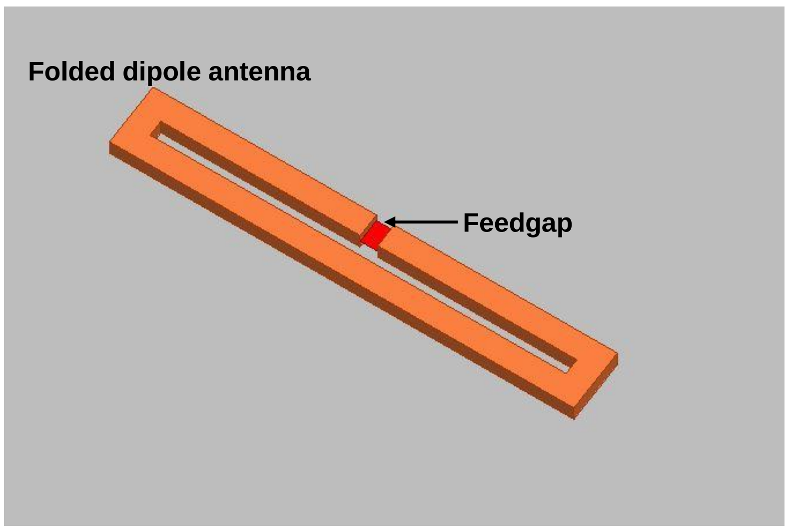

Figure S1| Folded dipole antenna with a feed gap excitation in HFSS

S.3 Analytical fitting to the measured data of double-folded and triple-folded dipole antennas

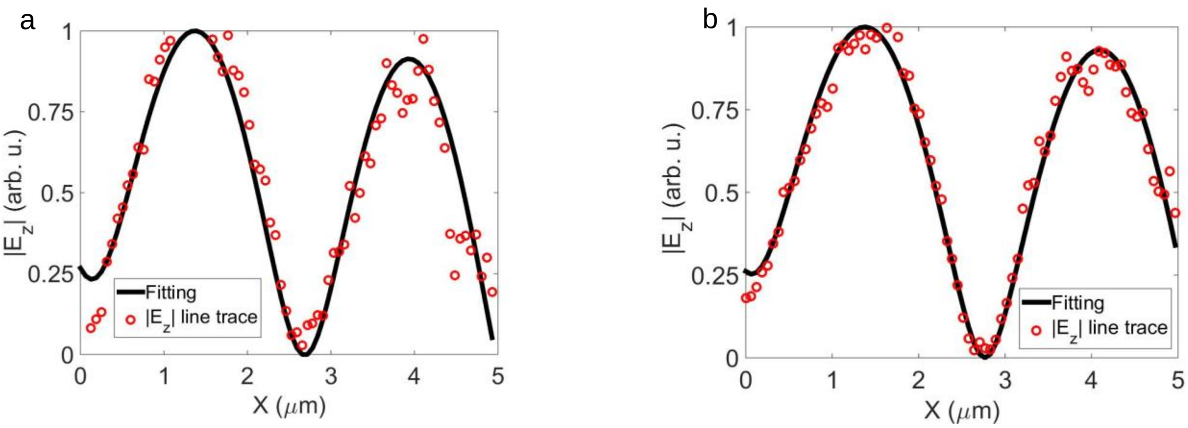

Figure S2| Analytical fitting to the measured data for the (a) doubled- and (b) triple-folded dipole antennas