Supporting Information for

Direct Conversion of Free Space Millimeter Waves to Optical Domain by Plasmonic Modulator Antenna

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Field enhancement derivation

The field enhancement describes the ratio between the incident electric field and the electric field in the slot

$$FE = \frac{E_{slot}}{E_i}. \tag{S1}$$

The amount of energy the antenna converts to the electric field in the slot E_{slot} can be derived from the antenna's effective aperture

$$A_{eff} = \frac{\lambda_{RF}^2}{4\pi} G_R, \tag{S2}$$

where λ_{RF} is the incident wavelength and G_{R} is the antenna gain. The time average power $\langle P_R \rangle$ collected by the antenna is given by the power intensity S and the effective aperture,

$$\langle P_R \rangle = S \cdot A_{eff} = \frac{E_i^2}{Z_0} \cdot \frac{\lambda_{RF}^2}{4\pi} G_R. \tag{S3}$$

We can express the voltage drop across the antenna slot by

$$\mathrm{V}_{slot,eff} = \sqrt{\langle P_R \rangle \cdot Z_d} = \sqrt{\frac{E_i^2}{Z_0} \cdot \frac{\lambda_{RF}^2}{4\pi} G_R \cdot Z_d} = E_i \cdot \sqrt{Z_d} \cdot \sqrt{\frac{\lambda_{RF}^2 G_R}{4\pi Z_0}}, \tag{S4}$$

where Z_{d} is the device impedance defined as the ratio between the voltage and current seen by a port placed in the plasmonic slot and Z_0 is the impedance of air. The electric field in the slot is found by dividing the voltage across the slot by the slot width

$$E_{slot} = \frac{\mathrm{V}_{slot,eff}}{w_{slot}}. \tag{S5}$$

This then leads to the field enhancement

$$FE = \frac{E_{slot}}{E_i} = \frac{\sqrt{Z_d}}{w_{slot}} \cdot \sqrt{\frac{\lambda_{RF}^2 G_R}{4\pi Z_0}}. \tag{S6}$$

Field enhancement simulation

We performed full-wave simulations of the plasmotenna using a commercial FEM software. We investigated the device impedance and its impact on the field enhancement. From Eq. (1) in the main text, it is expected that the device impedance is maximal at the maximum field enhancement. Figure S1 shows the simulated device impedance for a wide range of frequencies. We note three significant points. In resonance the imaginary part of the impedance is zero. From Figure S2 we can observe two resonances (points A and B). The first resonance at 38 GHz corresponds to the half-wave resonance of the structure (point A). The real part of the impedance is 60 Ω, which is very close to what one would expect for a half-wave dipole antenna. The second resonance occurs at 55 GHz and corresponds to the full-wave resonance of the structure (point B). The real part of the impedance now is much higher. However, the maximum point of the real impedance is slightly shifted from the resonance (point C). The frequency ratio between the half wave resonance and full wave resonance differs from the value 2 due to the frequency dependent material parameters and losses.

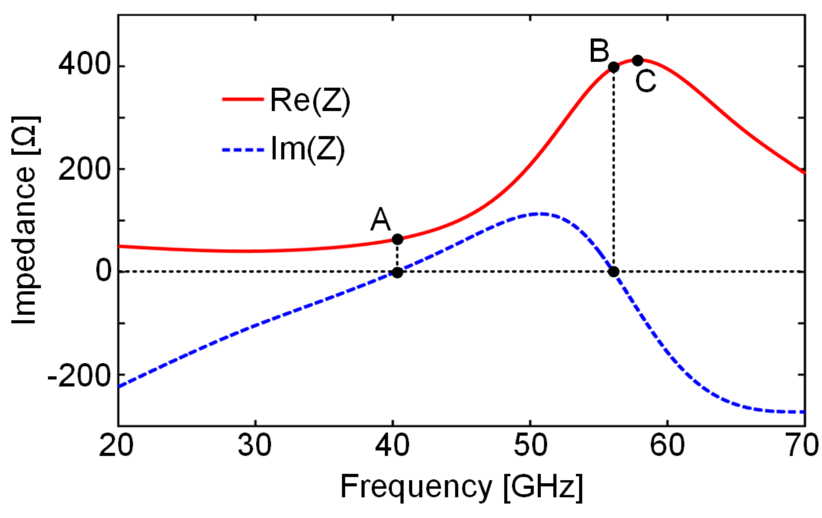

Figure S1. Simulated device impedance of the device with a slot width of 75 nm.

We simulated the field enhancement for the same structure. The simulation was set up such that a 1 V/m plane wave polarized parallel to the antenna arms was incident on the structure. We recorded the electric field in the slot with a field monitor positioned in the center of the PPM. Figure S2 shows the field enhancement as a function of the frequency. A maximum enhancement is observed at the frequency indicated by point B, which corresponds to the full wave resonance of the device.

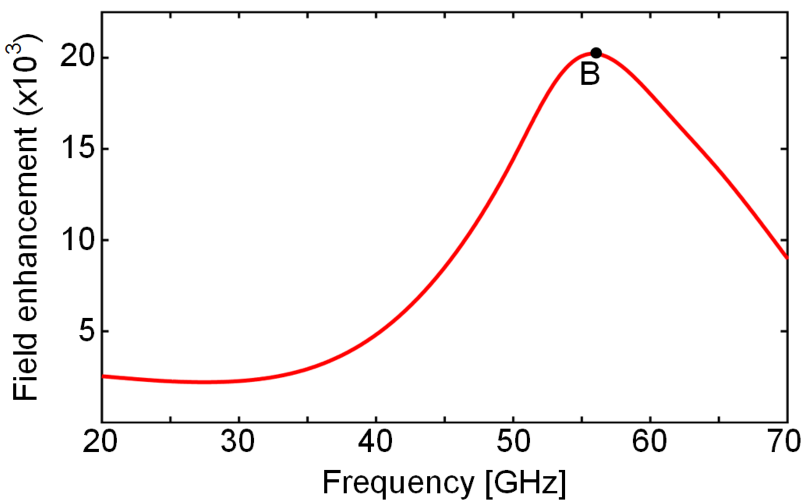

Figure S2. Simulated field enhancement of the device with a slot width of 75 nm.

Device sensitivity measurement

The optical response of the device for different incident electric fields was measured. Figure S3 shows the measured modulation index versus the incident electric field (red triangles). A linear fit (black curve) shows the linear dependence of the device. This is as expected from the linear electro-optic effect (Pockels effect).

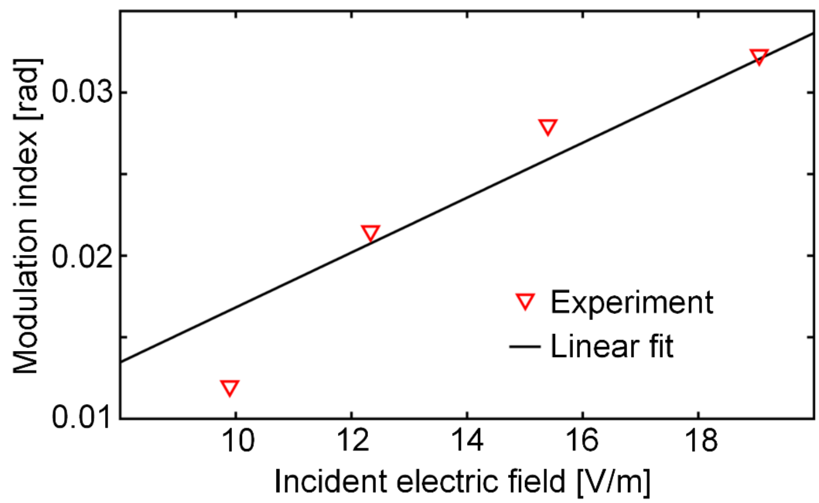

Figure S3. Measured optical response for different incident electric fields (red triangles). The black curve shows the linear fit of the experimental data.