Transparent Metallic Fractal Electrodes for Semiconductor Devices

Supplementary Information

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Analysis of the polarization response of a linear grating over different substrates

For the gratings shown in Figure 1 of the main text and for both polarizations and all substrates, abrupt features can be observed in the transmission spectra. These abrupt changes can be attributed to the emergence/disappearance of diffracted orders. Their occurrence remains even after replacing Al with a perfect electric conductor (PEC) and in the case of Al, excitation of surface plasmons does not considerably affect the transmission spectra. A comparison between an Al grating and a PEC grating is given in Figures 1S – 3S.

For the free-standing grating shown in Figure 1 of the main text, ±1 diffraction orders are excited along the grating-air interface when $\lambda_0 = P = 450$ nm, These are known as a Rayleigh-Wood's anomaly ($\sin\theta_m = m(\lambda_0/n)/P$ where θ_m is diffraction angle, m is diffraction order and n is index of substrate). For TM polarization at 450 nm, the polarization of the incident field evokes a strong interaction of this surface wave with Al nanowires through the excitation of localized surface plasmon resonances (LSPR) on individual nanowires, which explain the small peak seen in metal loss at 450 nm in all cases. For TE polarization, this wavelength corresponds to the point of maximum transmission. The boundary condition for TE polarization along the grating-air interface imposes the minima of the field to be located on the nanowires. This minimal overlap of the evanescent surface wave and metallic nanowires allows almost perfect coupling from the incident field into the outgoing field. For $\lambda_0 < P$ and for both polarizations, both zero-order and ±1 diffraction orders exist in transmission and reflection of the freestanding grating, however, for $\lambda_0 > P$, ±1 diffraction orders cannot be excited and optical energy is transferred only through the zero-order mode.

For the gratings on glass and for both polarizations, there is another change in transmission that occurs at around $\lambda_0 = 650$ nm. This wavelength corresponds to the excitation of ±1 diffraction orders along grating-glass interface and is red-shifted from 450 nm by the glass refractive index. Here again for TM polarization, the surface wave strongly interacts with nanowires at the glass-Al interface through the excitation of LSPR, which is accompanied by a small peak in metal loss.

For 450 < λ_0 < 650 nm, ±1 diffraction orders are present in transmission into glass, but not in reflection in the air. For λ_0 < 450, ±1 diffraction orders present both in reflection and transmission. For λ_0 > 650 nm, zero-order mode transmission dominates.

For the Al grating on silicon, transmission is lower than previous cases because bare silicon is highly reflective in this wavelength range (3.5< n_{Si} <6). For TE polarization, except for the initial step-rise, the transmission is relatively flat. The reason is that as the grating approaches cut-off at higher wavelengths, the silicon reflection also decreases. The metal loss peak around 800 nm is due to intrinsic Al loss (a maximum in ε''_{Al}) at this wavelength.

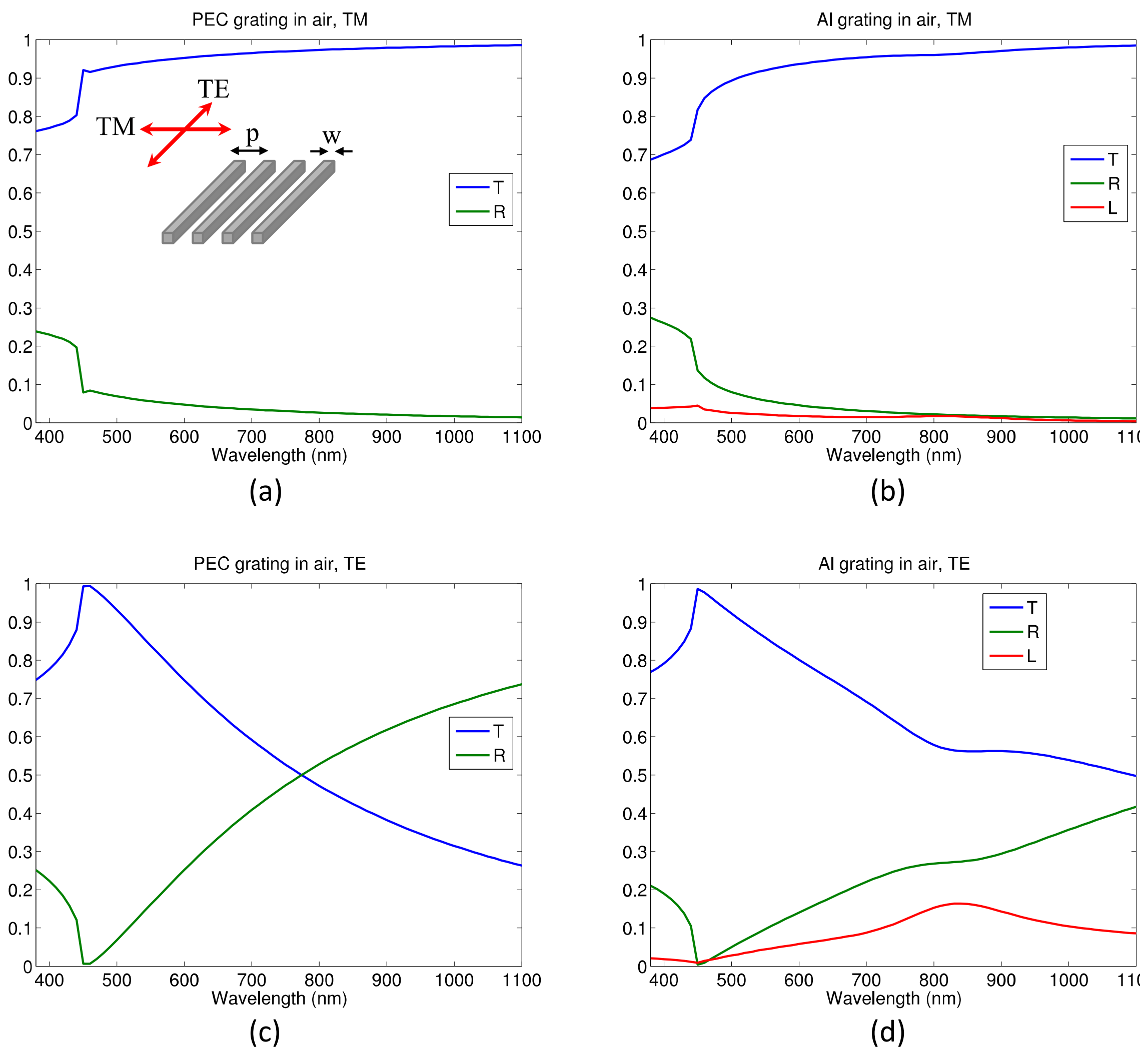


Figure 1S. Transmission, reflection, and loss in metal wires of a freestanding (a) PEC grating for TM polarization (b) Al grating for TM polarization (c) PEC grating for TE polarization and (d) Al grating for TE polarization. Blue curves correspond to transmission, green curves to reflection, and red curves to loss in metal wires (P = 450 nm, w = 100 nm, h = 40 nm)

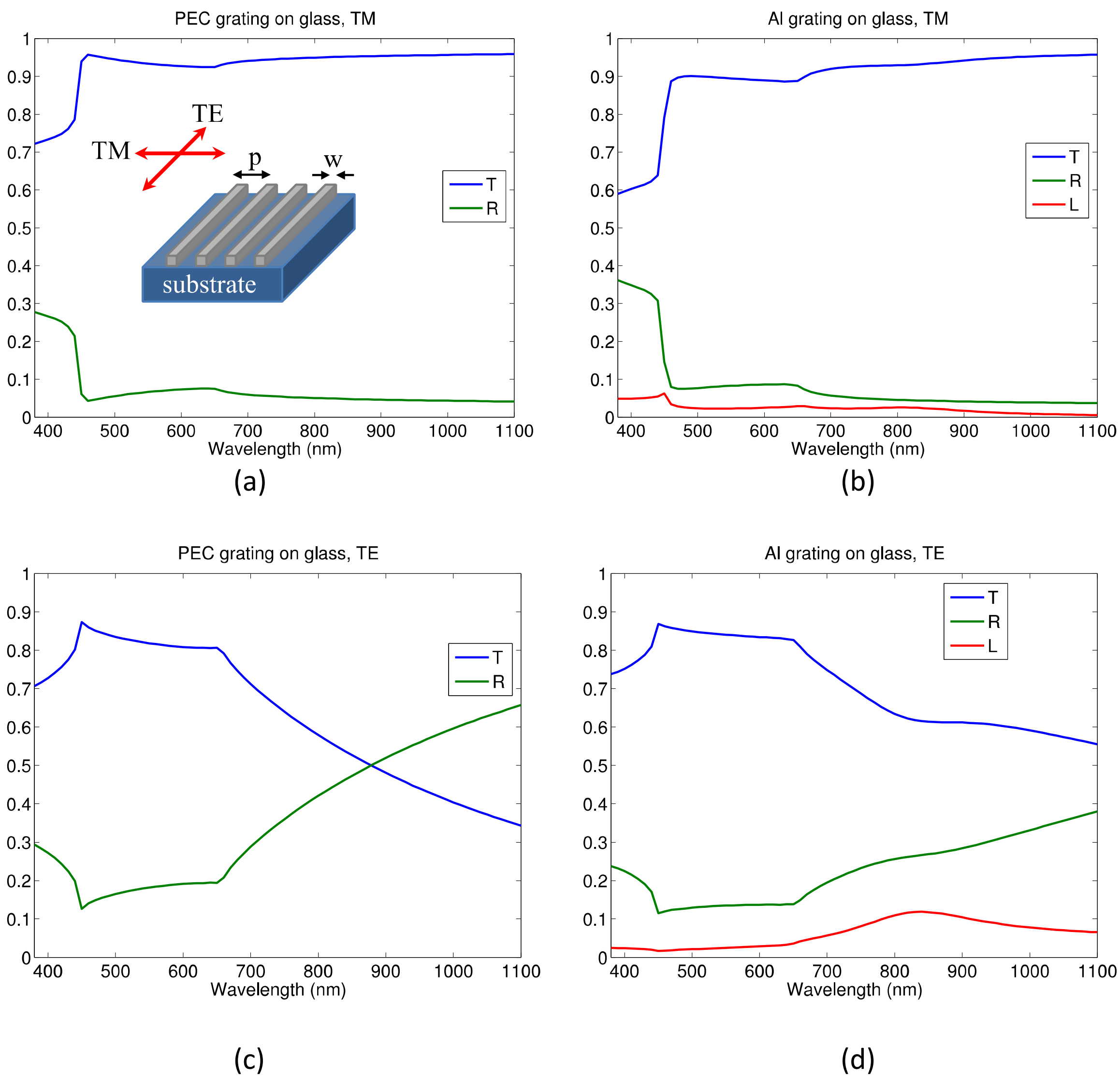


Figure 2S. Transmission, reflection, and loss in metal wires of a PEC or Al grating on a glass substrate. (a) PEC grating for TM polarization (b) Al grating for TM polarization (c) PEC grating for TE polarization and (d) Al grating for TE polarization. Blue curves correspond to transmission, green curves to reflection, and red curves to metal loss. Grating geometry parameters are the same as in Figure 1S.

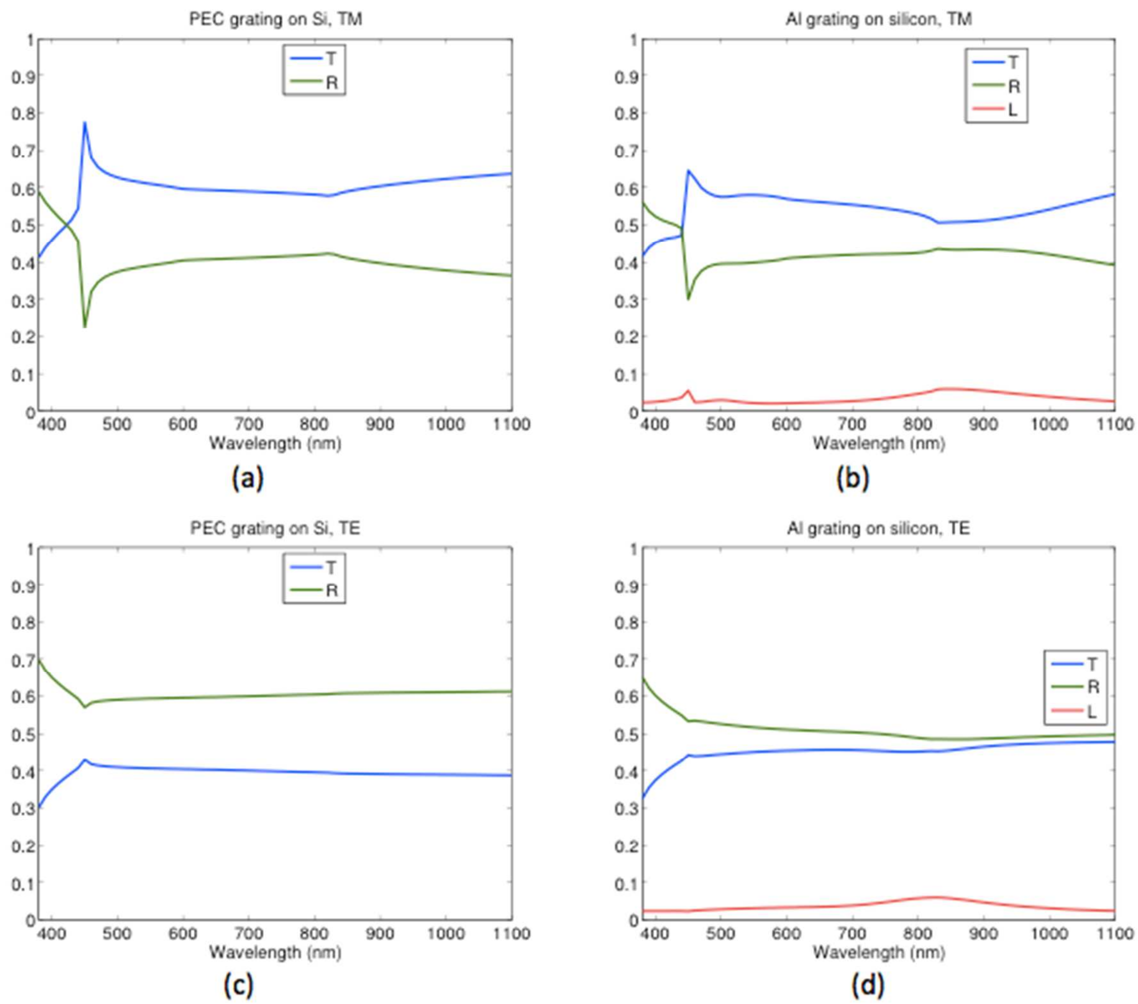


Figure 3S. Transmission, reflection, and loss in metal wires of a PEC or Al grating on a silicon substrate. (a) PEC grating for TM polarization (b) Al grating for TM polarization (c) PEC grating for TE polarization and (d) Al grating for TE polarization. Blue curves correspond to transmission, green curves to reflection, and red curves to metal loss. Grating geometry parameters are the same as in Figure 1S.

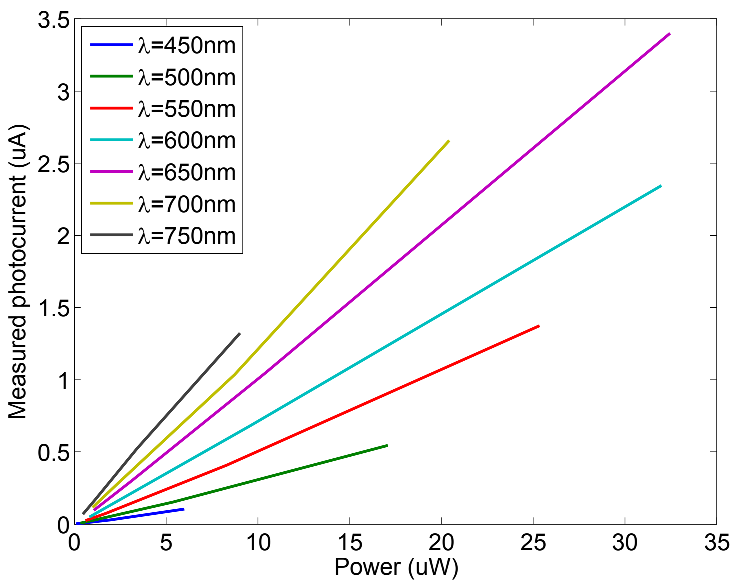
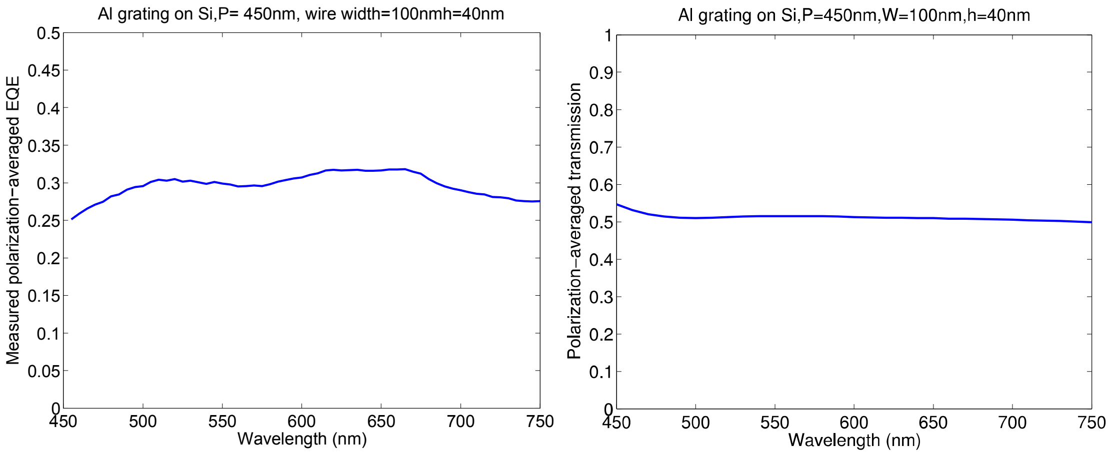


Figure 4S. Measurements of the photocurrent versus incident laser power show a linear dependence at various wavelengths across the considered spectral range. The photocurrent is measured at the center of a 12 µm x 12 µm Si box patterned on the reverse-biased electrode of the back-to-back Schottky detector.



(a) (b)

Figure 5S. (a) Measured polarization-averaged external quantum efficiency (EQE) for the Al grating on silicon with geometry parameters given in Figure 3 of the main text. EQE is calculated by multiplying the measured responsivity by $hc\ /\lambda_0 e$ (b) Simulated polarization-averaged transmission T for the grating in (a). Both the EQE and transmission are more-or-less wavelength-independent. Under the assumption that all of the light is absorbed in the device, it can be concluded that the internal quantum efficiency (IQE) also exhibits only a weak wavelength independent (EQE = A x IQE ≈ T x IQE), where A is the absorbed fraction of incident photons. This assumption is reasonable based on the relatively short absorption depth of 10 μm in Si at 750 nm.

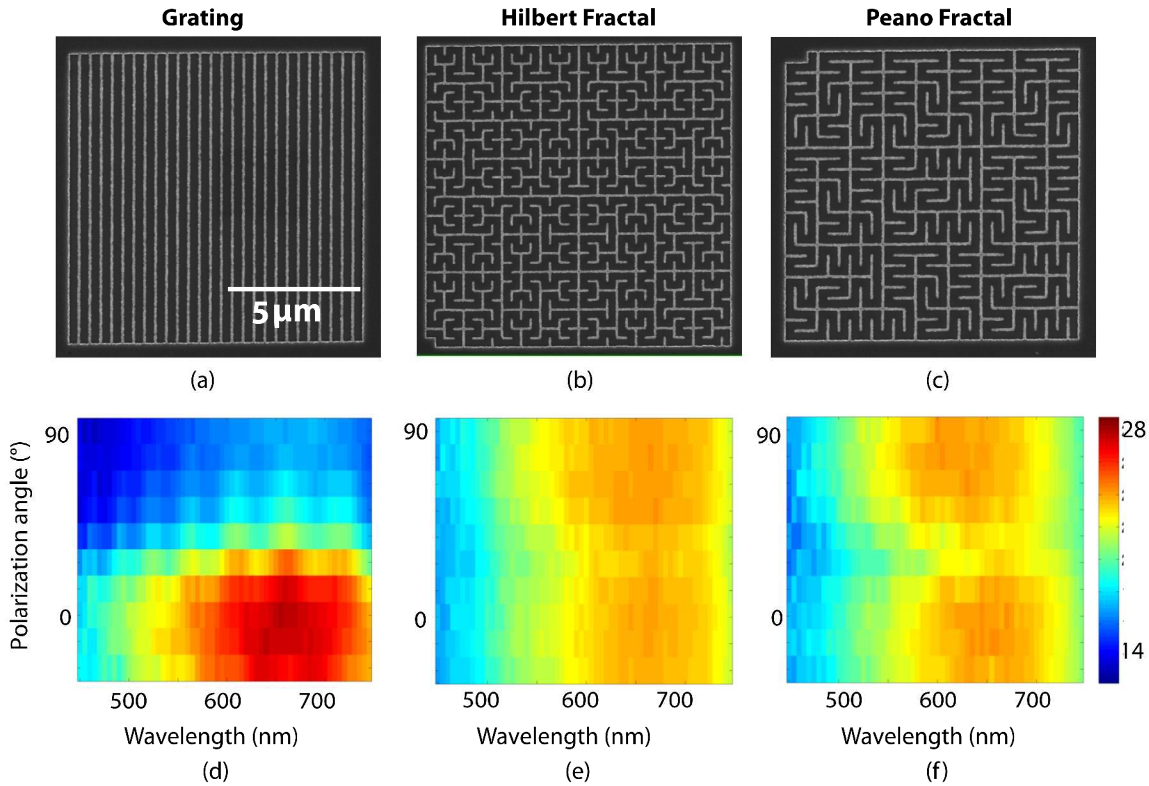


Figure 6S. SEM images of Al electrodes patterned with (a) a linear grating (b) a Hilbert fractal (c) a Peano fractal. The width of the Al nanowires is 100 nm in all images. The periodicity of the grating and the grid and *p* parameter defined in Figure 2 of the main text for fractals is 450 nm. (d-f) Measured responsivity maps as a function of polarization and wavelength normalized to the responsivity of a device with an unpatterned 40-nm-thick Al electrode. Each responsivity map corresponds to the electrode shown above it in the first row. 0° and 90° polarization angles correspond to incident electric field being normal (TM) and parallel (TE) to the grating nanowires respectively.