Multi-Resonant Bianisotropic Metagratings for Ultra-Efficient Diffraction of Mid-Infrared Light

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Abstract:

We demonstrate that a bianisotropic metamaterial supporting four optical resonances of the appropriate symmetry can be used as a building block for achieving perfect diffraction of mid-infrared radiation. We design and experimentally realize such bianisotropic metamaterials. We show that near-perfect diffraction to the $^{+}1^{st}$ diffraction order is possible, while other orders are suppressed, in the mid-infrared spectral region.

Summary of Research:

We experimentally verify the viability of the "perfectly" diffracting metagrating in the mid-IR spectral region [1]. The geometric dimensions of the designed structure and corresponding diffraction spectra have been simulated using a finite-element-method software. An undoped, double-side-polished wafer (Ultrasil, Inc.) with a device layer of 2.7 µm and a buried oxide layer of 1.0 µm was cleaned in acetone and isopropyl alcohol (IPA) and coated with two layers of positive electron beam resist: 100 nm of PMMA 950 on top of the 200 nm of PMMA 495k, baking the resist at 170°C for 15 min after each coating step. The desired pattern was exposed over the substrate at 1000 µC/cm^2 (JEOL 9500FS) and developed in MIBK:IPA 1:3 solution for 75 sec, with consequent rinsing in IPA. A 60-nm-thick Cr hard mask was deposited using electron beam evaporator at a rate of 3 nm/min. After liftoff in sonicated acetone (60 sec), HBr plasma dry etching of silicon down to the 1-µm-thick buried oxide layer was carried out (Oxford Cobra), leaving the desired pattern carved in the device layer. As the last step, the residual Cr mask was removed with a Cr wet etch. The patterned area of each metagrating was (1.5 mm)^2. A scanning electron microscope image of the best-performance sample is given in Fig.1(a).

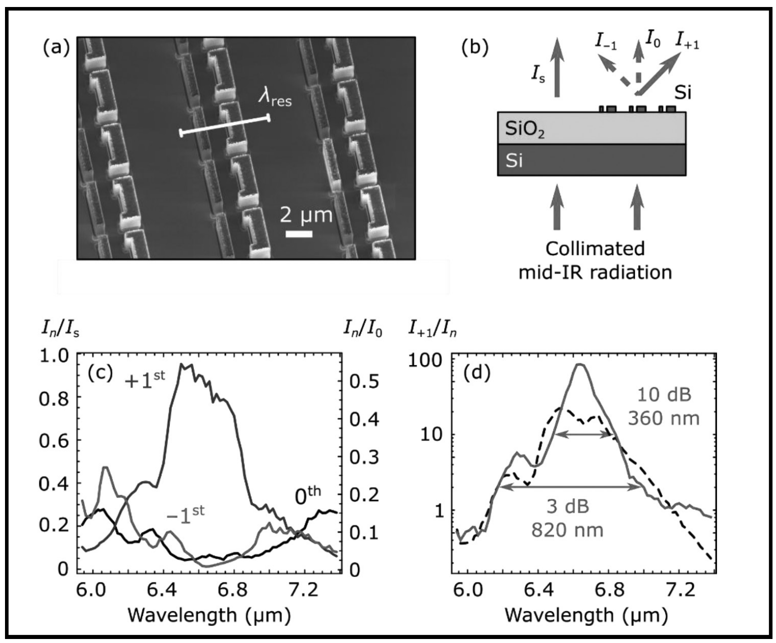

Figure 1: (a) SEM image of the best-performance metagrating. (b) Schematic of the experiment. The three measured diffraction orders in transmission, and the bare substrate transmission, are indicated by arrows. The targeted diffractive order is the $^{+}1^{st}$. (c) Diffraction efficiency of the $^{+}1^{st}$, 0^{th} and $^{-}1^{st}$ transmitted diffraction orders normalized to the bare substrate transmission measured as the function of the wavelength. The axis on the right shows absolute diffraction efficiency as normalized to the incident field intensity. (d) Diffraction contrast spectra I_{+1}/I_0, (dashed line) and I_{+1}/I_{-1} (solid line).

The normalized diffraction efficiency I_{+1}/I_s of the fabricated metagratings, defined as the ratio of the transmission I_{+1} into the targeted diffraction order to the transmission I_s through the bare Si/SiO_2 substrate, was experimentally measured. Such normalization is necessary because of the substantial (43%) amount of light experiencing reflection at the high-contrast flat Si-air and Si-SiO_2 interfaces. This artefact is due to the chosen material platform (SOI), and can be overcome by using, for example, Si-on-sapphire wafers.

A quantum cascade laser (Daylight Solutions MIRcat) was used as a source of highly collimated monochromatic tunable quasi-CW mid-IR radiation, as shown in Figure 1(b). The laser beam was softly focused with a 50-mm-focal-length lens to a 200 μm diameter spot from the back side of the wafer. The intensity of the diffracted light was measured using a pyroelectric array camera (Ophir Spiricon Pyrocam III) by integrating the intensity over the entire array. For each wavelength, the intensities of the $^{+}1^{st}$, $^{-}1^{st}$ and 0^{th} transmitted diffraction orders (I_{+1}, I_{-1}, and I_0) were detected, and the $^{+}1^{st}$ and $^{-}1^{st}$ orders were also detected studied in reflection. The reflected diffraction orders were beyond detection limit. The bare substrate transmission I_s for the efficiency normalization of the diffracted orders was measured by passing the beam through the unstructured part of the wafer, where the device layer is etched away.

The normalized diffraction efficiencies for all transmitted diffraction orders are plotted in Figure 3(c) as a function of the incident wavelength of light. Within our experimental margin of error, the peak grating efficiency at 6.45 μm is of order 95%. Note from Figure 1(c) that the diffraction efficiency into the $^{-}1^{st}$ order is even smaller than into the 0th order. Such an enormous asymmetry between the $^{-}1^{st}$ and $^{+}1^{st}$ orders is due to the bianisotropic nature of the metasurface.

Another important characteristic of the diffraction efficiency is the contrast between the $^{+}1^{st}$ and 0^{th} orders, defined as I_{+1}/I_0, and the $^{+}1^{st}$ and $^{-}1^{st}$ orders, defined as I_{+1}/I_{-1}.

The plots of these quantities shown in Figure 1(d) indicate that the contrasts approach 20 and 80, respectively. Note that the high contrast is achieved for a fairly broad band of mid-IR wavelengths: 260 nm for 10 dB rejection, and 820 nm for the 3 dB rejection of the $^{-}1^{st}$ diffraction order.

References:

[1] Z. Fan, M.R. Shcherbakov, M. Allen, J. Allen, G. Shvets, "Perfect Diffraction with Bianisotropic Metagratings," arXiv:1802.01269 (2018).