Infrared Filtering via Sub-Wavelength Gratings for Hyperspectral Imaging

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Abstract:

Fabry-Perot cavities are an attractive method of infrared filtering, provided they are made of broadband, lossless reflectors. A long wavelength infrared region (LWIR, 8-12 μm) broadband reflector is demonstrated using a high-index contrast sub-wavelength grating (HC-SWG) based on a suspended silicon system. The expected grating field response was simulated using COMSOL Multiphysics to exhibit greater than 90% reflectance in the LWIR, for transverse magnetic polarization. An un-switched C_4F_8/SF_6 reactive ion etch (RIE) was characterized, and showed improved sidewall profile compared to previously used etch chemistry. Fabricated gratings demonstrate greater than 85% reflectance between 8 μm and 14 μm, with the response agreeing well with simulations incorporating as-built dimensions.

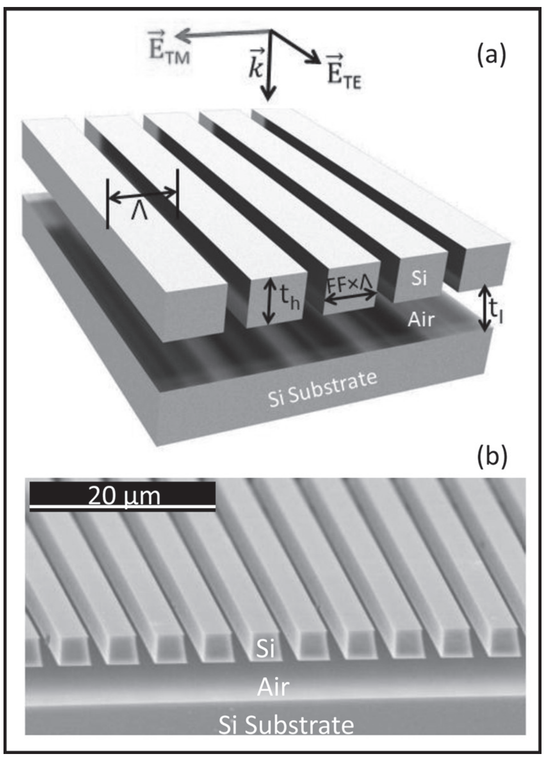

Figure 1: a) A suspended silicon grating schematic, and b) A representative fabricated suspended silicon grating.

Introduction:

Hyperspectral techniques are needed to advance to the next generation of thermal imaging systems. A hyperspectral image contains the electromagnetic spectrum for every point in an imaging plane, providing a "fingerprint" for different objects. These fingerprints improve object discrimination, which is useful in a wide array of applications including satellite analysis of climate change, military surveillance, and biological and chemical sensing. Hyperspectral images are formed from intensity acquired at each wavelength, which requires narrowband filters such as interference-based Fabry-Perot cavity filters. A Fabry-Perot cavity is composed of two parallel reflectors separated by a set distance, and transmits light when a standing wave can be established between the two mirrors. To ensure highly efficient and selective filters, the reflectors must exhibit very high reflectance and be non-absorbing. In this work we designed, fabricated and characterized a low loss reflector using a high-contrast grating.

It was first shown by Mateus [1] using a system of poly-Si gratings (n = 3.48) on top of SiO_2 (n = 1.4) that high-contrast-gratings could function as broadband and lossless reflectors. "High-index-contrast" refers to the large difference between the refractive indices of the grating and surrounding media. Figure 1 shows a schematic of a high-contrast-grating with dimensions and polarization defined as well as a corresponding fabricated grating. The parameters necessary to optimize the response are the grating period (Λ), fill factor (FF), which is the ratio of a grating's width to the period, and thicknesses of the high and low index layers, (t_h and t_l).

Experimental Procedure:

We optimized the design of a silicon (n = 3.4) grating suspended in air (n = 1) using commercial finite element analysis software for transverse magnetic (TM, electric field directed along the grating periodicity) polarized light. A single grating period was used as the computational domain assuming periodic boundary conditions and material optical properties from Palik [2]. Iterative optimization showed an expected reflectance greater than 90% between 8 μm and 12 μm, an important spectral range for thermal imaging.

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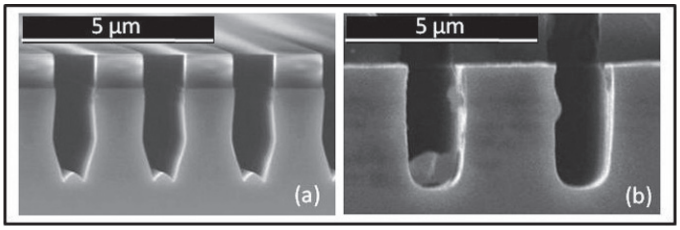

Figure 2: Grating cross-sectional profiles after a) H_2/HBr, and b) C_4F_8/SF_6 reactive ion etches.

We used a commercial silicon-on-insulator wafer as the platform for fabricating our suspended grating using photolithography and reactive ion etching (RIE). Subsequent wet etching of the sacrificial SiO_2 layer with hydrofluoric acid suspended the gratings as shown in Figure 1b. We characterized the grating response using polarization dependent Fourier transform infrared spectroscopy (FTIR) in transmission mode using an aperture to constrain the focused light.

Results:

We compared the sidewall profiles of a fluorine-based RIE chemistry (C_4F_8/SF_6) to a previously used bromide-based etch chemistry (H_2/HBr) using scanning electron microscopy (SEM). The fluorine-based plasma etching improved sidewall profiles over the bromide-based chemistry, as shown in the micrographs of Figure 2. The sidewalls produced by the C_4F_8/SF_6 RIE are more vertical and have minimal bowing compared to the H_2/HBr profiles, both of which are expected to improve the structure response. We further characterized the etch rate dependence on open area of the C_4F_8/SF_6 RIE as shown in Figure 3, which shows larger periods, with larger open areas, exhibit higher etch rates. These results were used to optimize the grating fabrication process.

FTIR characterization of our gratings indicated less than 15% of incident light was transmitted in the spectral range of 8-14 μm. The expected transmittance, obtained from simulation with the as-built dimensions of the structure (Λ = 5.3 μm, FF = 0.7, t_h = 3.3 μm, and t_l = 4.3 μm) agreed well with the experimental transmittance, indicating the reflectance may be approximated as R+Loss = 1-T, where the Loss term is small.

Figure 4 shows the derived reflectance and simulated response of the gratings as well as the reflectance of a control silicon wafer. The derived reflectance agrees well with the simulation further suggesting loss in the materials does not significantly affect the response. The agreement between the expected reflectance and experimental data indicate the grating acts as a broadband reflector, with greater than 85% reflectance between 8 μm and 14 μm.

Conclusions and Future Work:

We fabricated and characterized a high-contrast grating reflector that exhibits greater than 85% reflectance between 8 μm and 14 μm. We improved the fabrication procedure using a C_4F_8/SF_6 etch chemistry, which improved sidewall profiles over a previously used H_2/HBr etch. Future work includes design and fabrication of a polarization independent high-contrast-grating consisting of a two-dimensional layout. Initial design optimization shows a response with greater than 80% reflectance between 9 and 12 μm.

Acknowledgements:

I would like to thank my mentor Justin Foley, Principal Investigator Professor Jamie Phillips, the staff of the Lurie Nanofabrication Facility, especially Shawn Wright, Greg Allion, Kevin Owen, and Vishva Ray, the National Nanotechnology Infrastructure Network REU Program, especially Brandon Lucas and Trasa Burkhardt for their help, and the National Science Foundation for making this research possible.

References:

[1] C.F.R. Mateus, M.C.Y. Huang, L. Chen, C.J. Chang-Hasnain, and Y. Suzuki. "Ultrabroadband Mirror Using Low-Index Cladded Subwavelength Grating," IEEE Photonics Technol. Lett. 16, (2004).

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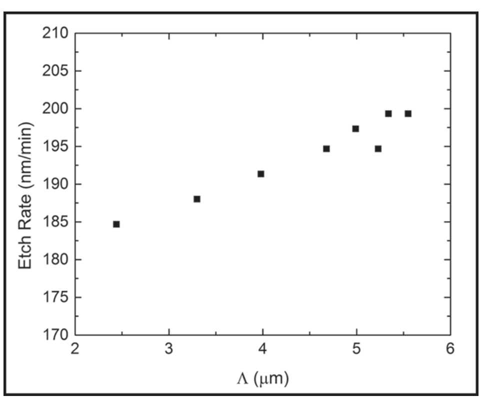

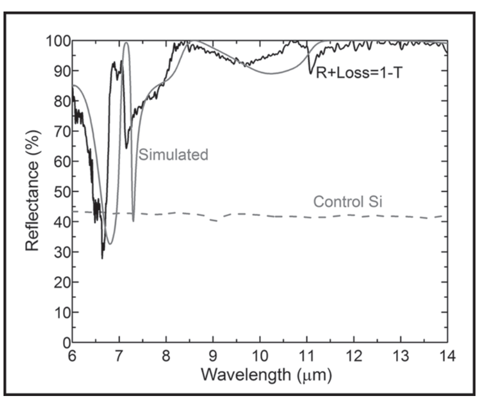

Figure 3, left: Etch-rate dependence on period for C_4F_8/SF_6 reactive ion etching.

Figure 4, right: Derived experimental reflectance spectra, simulated reflectance of as-built structure, and the experimental reflectance of a control silicon wafer.