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Laser-Line Rejection or Transmission Filters Based on Surface Structures Built on Infrared Transmitting Materials

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ABSTRACT

Night vision and related thermal imaging systems play a critical role in the protection of our nation's security. These systems record images using video cameras designed for operation in the infrared (IR) region of the light spectrum. As with any imaging system, increased functionality and new information is gained when discrete portions of the observed light spectrum are analyzed separately using optical filters. Highly discriminating filters are needed to increase the sensitivity of atmospheric chemical sensors, to enable multi-spectral imaging and secure laser communications links, and to protect imaging systems from damage due to attack by high power laser weapons.

Today, the performance of IR light filters is inadequate for many applications. Filters capable of efficient rejection of multiple discrete wavelength bands, combined with high transmission for wavelengths outside the rejection bands, do not exist. A new type of narrow-band optical filter capable of protecting critical imaging systems from attack from laser weapons operating at multiple wavelengths, is being developed. Based on rugged surface-structure wave-guide resonant holograms, the new filters will be capable of rejecting better than 99% of IR light within each notch, while maintaining the same level of transmission outside each notch covering a broad range of the IR spectrum.

The theory, design and fabrication of surface structure, laser-line rejection and transmission filters built upon infrared transmitting materials, will be described. Optical performance data for prototype structures will be presented.

Keywords: Infrared Optical Filters, Surface Structures, Wave-guide Resonant, Sub-Wavelength, Laser Hardening

1. INTRODUCTION – FILTER APPLICATIONS

Band-pass and rejection filters are needed for a wide variety of military and commercial applications that make use of infrared light. A primary application requiring narrow-band filters is in military Forward Looking Infrared, or FLIR systems. In a FLIR, night-vision imaging system, broad-band infrared light is collected through an optical lens and projected onto an array of detectors which in turn produce an electronic signal for display on a monitor. FLIR systems can be blinded when too much energy is collected by the lens systems. Often this excess energy derives from discrete wavelength sources such as a laser radar or weapon system. Filters can be used to reject such high power signals while maintaining high transmission of the desired wavelength region. In addition, FLIR cameras can employ filters to create multi-color images – a concept known as multi-spectral imaging.

Narrow-band transmission filters are useful for detecting airborne chemicals or pollutants. Target chemicals such as ozone and carbon dioxide will emit infrared energy with a specific wavelength that depends on the chemical's temperature and position in the atmosphere. An array of discrete narrow-band filters can be used to detect a great number of chemicals simultaneously[1].

A free-space, point-to-point laser communication system employing multiple discrete wavelengths carrying amplitude modulated signals, is realized using narrow-band filters. Such a system operating in the long- or mid- wave infrared region (LWIR: 8-12 micron, MWIR: 3-5 micron) can carry a huge amount of secure, line-of-sight information in a manner identical to the wavelength division multiplexed (WDM) signals carried by near infrared light traveling within commercial fiber-optic cables.

Narrow-band reflection filters can be used as feedback elements in laser cavities. One of the most common high power lasers used for metal cutting and welding, is a carbon dioxide gas laser operating at a LWIR wavelength of 10.59 microns. Wavelength selective mirrors, or rejection filters, can be used to form the laser cavity rear reflectors. The

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reflection from such mirrors needs to be much greater than 99% due to the high powers typically generated (many tens of kilowatts[2]. Rejection filters can also be used for laser tuning by mechanically changing the orientation of the filter with respect to the laser cavity axis.

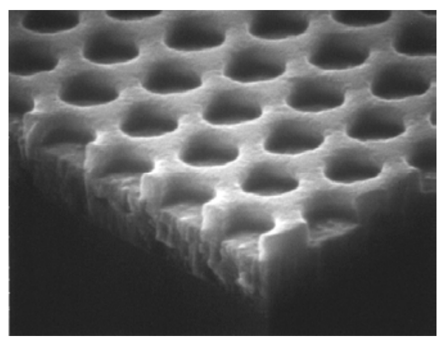
2. CONVENTIONAL OPTICAL FILTER TECHNOLOGY

Thin-film filter technology provides a conventional approach to producing narrow-band infrared filters. Alternating layers of high and low refractive index materials are deposited onto a substrate. Interference between light reflecting from each layer will add constructively for a narrow range of wavelengths, yielding a strong narrow-band reflection. Thin-film filters can achieve highly efficient filtering, however the cost of such filters is prohibitive when high reflectivity and narrow rejection bands are specified. For near IR (NIR: 1.3-1.6 micron) thin-film filters used in telecommunications, often a few hundred layers are needed to achieve the ultra-narrow bandwidths and rectangular filter profiles needed. For narrow-bandwidth MWIR or LWIR rejection filters, as many as 40 layers of thin-films are needed with a total thickness of about 30 microns[1]. (Transmission filters would require an even larger number of film layers). The use of graded index layers ("rugate" technology) can reduce the number and type of layers required at the cost of increased complexity, more difficult manufacturing, and no reduction of overall deposited layer thickness. In addition, thin-film filter transmission losses for wavelengths outside the filter band can be as high as 50% for longer wavelength infrared light in the MWIR or LWIR ranges[3]. Such losses would make the design of cascaded filter banks (a comb filter) impractical. Achieving multiple rejection bands from a single thin-film stack is highly complex and likely a practical impossibility. Lastly, thin-film filter layers are typically deposited by high temperature evaporation of the coating materials within a vacuum chamber, a costly process that is problematic for some temperature sensitive materials used in FLIR cameras.

Narrow band rejection can also be produced with existing surface structure gratings employing the optical phenomenon of diffraction. Grooves etched into the surface of an IR transmitting substrate, are repeated in an array with a groove spacing comparable to the wavelength of light desired. The grooves in the grating serve to diffract different wavelengths of light at different angles, spreading broad-band light over a large angular range. The position of a detector placed in this light field will sense only a narrow range wavelengths. Grating filters suffer from low rejection efficiency, typically below 90%, and from high transmittance losses for out of band light due to scattering and diffractive losses.

3. SUB-WAVELENGTH SURFACE STRUCTURE OPTICAL FILTER TECHNOLOGY

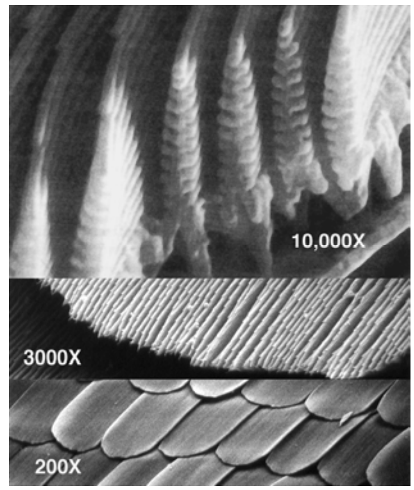
TelAztec's innovative filter technology, currently being developed for a variety of IR applications, offers a solution to the problems associated with filtering IR light by conventional thin-film or grating based techniques. Based on surface structure wave-guide resonant effects[4-14], sometimes referred to as zero-order diffraction, TelAztec's surface structure resonators create photonic band gaps for free space propagating optical beams. Surface texture holograms etched directly into a thin material layer deposited onto an IR transmitting substrate, are composed of microscopic features with dimensions much smaller than the wavelengths at which the filter is designed to operate. Features such as holes, cones, mesas, lines, and pillars arrayed across a substrate, function as individual resonators for a narrow range of light wavelengths. This light is trapped within the wave-guide where it interacts with the array of resonators and is reflected back with great efficiency. The size, shape, and composition of the resonators in the array determine the filter bandwidth, filter pass band profile, and center wavelength. A scanning electron microscope (SEM) image of a typical filter micro-structure, is shown on the right. Here an array of 250 nanometer (nm) diameter holes in a 180nm thick layer of tantalum pentoxide (Ta2O5) deposited on a fused silica substrate, serve to reflect 780nm wavelength light.



Wave-guide resonant structures readily produce narrow-band reflection. To achieve narrow-band transmission, wave-guide resonant structures are placed between highly reflecting broad-band mirror structures in a classic Fabry-Perot resonant cavity configuration. (This is directly analogous to placing a solid etalon within a laser cavity to produce "single-frequency" operation). Thin-film narrow-band transmission filters create Fabry-Perot cavities using stacks of non-absorbing dielectric materials[15]. A cavity resonance is obtained for light propagating in the longitudinal direction.

In contrast, structural wave-guide resonant filters are configured to create a resonance in both the longitudinal and transverse directions, effectively reducing the number of layers required to achieve narrow-band transmission. In Section 4 below, a model is given for a narrow-band MWIR transmission filter that uses just three material layers with a total thickness of just 1400nm. To attain equal performance in a thin-film filter design requires about 25 layers with a total thickness of over 8000nm.

Much of the literature available on wave-guide resonant transmission filters has been theoretical, with designs covering the visible and near infrared using dielectric materials, and designs for the microwave and millimeter wave regions employing metal-dielectric resonances[16-19]. The design has predominantly called for the structural resonator to be on the surface of, or embedded within, multiple-layers of dielectric thin-films. Our approach is based on an all structural resonator design which greatly simplifies the number of materials needed and yields a practical fabrication process.



Nature provides a design for another type of surface structure optical filter that utilizes just a single material layer. A brilliant metallic blue or violet color can be seen reflected from the wings of South American butterflies known by their species name, *Morpho*. The color is the result of multiple reflections from microstructures projecting from the wing. Tiny ribs in the structure are spaced about half a wavelength apart for blue light so that partial reflections from each rib will add constructively. All other wavelengths pass without reflection and are absorbed by the underlying wing structure. SEM micrographs of the wing structure are shown to the right. Three images are shown with increasing magnification. At 200 times magnification seen in the lower part of the image, individual scales can be seen. On each scale there exists long threads of material that in cross section contain the rib structure as seen in the top part of the image. There are as many as ten ribs on each side of a thread creating a large number of reflecting surfaces that account for the observed reflection efficiency – estimated at over 70%. With this type of structure, the filter bandwidth is determined by the number of ribs and is equal to approximately the reflected wavelength divided by the number of ribs – or about 45 to 50nm in the case of the *Morpho Rhetenor* butterfly shown. A thorough analysis of the butterfly wing structure and methods for fabricating similar structural filters was developed by one of TelAztec's founders, Dr. James J. Cowan. Dr. Cowan named his artificial butterfly structure "Aztec" after the microstructure's resemblance to stepped pyramids built by the Aztec Indians[20].

4. FILTER DESIGN AND PERFORMANCE MODELING

Sophisticated computer models have been developed to guide the fabrication of, and predict the performance of surface structure optical filters. Using a rigorous vector diffraction calculation, the software can predict the spectral reflectance and transmittance of infrared light through a user defined three-dimensional surface texture composed of multiple structured and uniform materials. The model accounts for arbitrary polarization states and light incident angles. Measured data for the optical constants of a library of materials is included. As further demonstrated below and in the Measured Performance Section 7, our modeled performance has proven to be a good match to measured filter performance. Structural filters with extremely low loss both in and out of the pass band, have been demonstrated for very NIR biological sensors, NIR telecommunications, and LWIR multiple laser-line rejection. This ability to predict device behavior and to analyze the impact of fabrication errors is essential to the practical commercialization of surface structure filter technology.

Technical Approach: There are two surface structure filter design schemes that have been used to realize prototype narrow-band filters operating in the near and long-wave infrared. The first involves the use of a uniform wave-guide layer in combination with a sub-wavelength surface relief structure that couples a narrow range of light into and traps that light within the wave-guide. The right hand plot in Figure 1 shows a cross section of this design where a uniform layer of Ta_2O_5 is used as the wave-guide layer. The structural layer is etched into the external surface layer, which in the case of Figure 1 is the same layer of Ta_2O_5, and the entire filter structure is supported by a sapphire substrate. The second design creates a structured wave-guide layer, e.g. the microstructure is defined throughout the wave-guide layer, as shown in the left hand plot in Figure 1. This latter design typically yields more narrow filter bands suitable for the less than 1nm bandwidths needed for telecommunications and chemical sensors in the NIR. However, it is more difficult to design filters with high isolation (low out-of-band reflection) with the unified waveguide and surface structure approach. The former design provides another layer that can be optimized to help suppress out-of-band reflections and, in a similar manner, the wider bandwidths needed for LWIR applications are more readily achieved.

Design Examples: Figure 1 below shows the predicted performance of a surface structure filter designed to reflect 780nm light in the NIR. Two plots are shown comparing the resonance obtained from surface structures fabricated in a layer of Ta2O5 (n_2=2.07) deposited on a sapphire (n_3=1.65) substrate. Cross sections of the modeled structures are shown for each plot. The models predict the wavelength and amount of light reflected out of broad-band light incident along the normal to the plane of the structures. For the plot on the left, a two-dimensional array of 220nm diameter holes were modeled with a grid spacing (Λ) of 470nm and a depth of 215nm. The incident environment was air (n_1=1.0). A narrow-band reflection centered at 780nm is predicted with a bandwidth at half maximum (FWHM) of about 5nm. Outside the rejection band a reflectance of about 5 to 10 percent is predicted. This out-of-band reflection can be suppressed to levels below 0.5% by modifying the structure parameters. The plot on the right side of Figure 1 shows a 780nm resonance optimized for high out-of-band isolation. The anti-reflecting properties of the structure were optimized by increasing the size of the holes in the Ta2O5 layer and decreasing the depth of the holes so that some Ta2O5 material remains between the hole structure and the sapphire substrate. In both cases the predicted transmission through the structure is the inverse of the reflectance curves except for some additional loss due to diffraction at wavelengths below 750nm. In both cases the depth of the notch in transmission is below 0.05%, or –33dB.

The narrow-band filters designed in Figure 1 are particularly useful as filters in data storage (CD) applications, as signal amplifiers in a highly sensitive chemical detector[21], and as temperature sensors that operate in extreme environments.

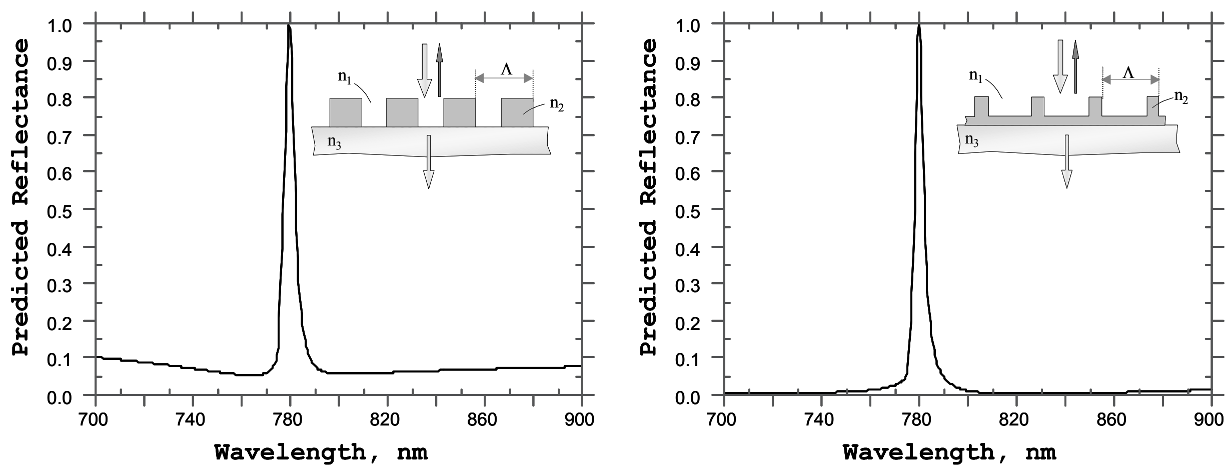


Figure 1: Predicted reflection of NIR light from surface structure filters designed to resonate at 780nm.

Exceptionally narrow bandwidth structural filters are needed for filtering the laser sources used for optical communications. With fiber-optic telecommunications, the laser wavelengths employed are in the NIR centered typically around 1550nm, and the filter bandwidths required are less than 0.5nm. The Fabry-Perot shape of the filter functions shown in Figure 1, limits the range of wavelengths that are passed or rejected without loss. To widen the filter band and achieve "flat-top" performance, thin-film filter designers employ multiple Fabry-Perot cavities each made up of stacks of thin-films, often adding up to hundreds of layers. Structural filters in contrast can achieve flat-top performance with just two structural layers arranged in a resonant cavity configuration[21,22]. Figure 2 shows the predicted performance of a structural filter designed to match the specifications for a standard 100 gigahertz (GHz) filter used in fiber-optic telecommunications. A cross sectional diagram of the modeled structure is also shown in the Figure. The design again employs Ta2O5 as the structural waveguide material consisting of an array of holes arranged in a hexagonal grid pattern with a spacing, or pitch, of 1034nm. The waveguide structures are supported by fused silica substrates (n_3=1.45), and the cavity is filled with air. The filter operates on free-space propagating light incident normal to the filter substrates. As with other filter technologies, the filter band can be tuned over a small range by changing the angle-of-incidence of the light. The filter band can also be tuned electrically by incorporating an electro-optic material within the resonant cavity or by fabricating the waveguide structures with an electro-optic material[22].

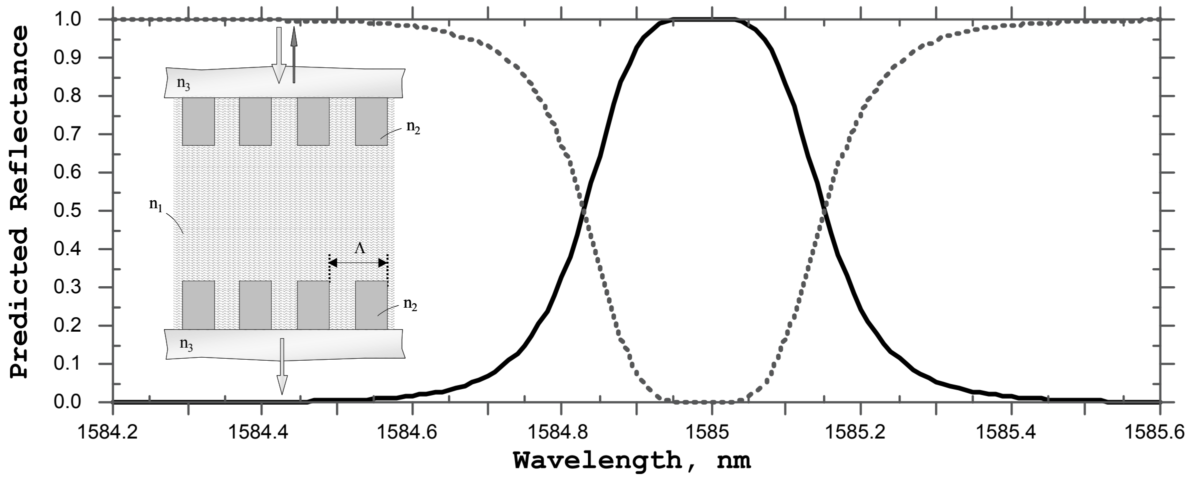


Figure 2: Predicted performance of a 0.2nm wide (100GHz) NIR surface structure filter configured with a resonant cavity.

Another type of telecommunications filter requires flat-top performance over a much wider bandwidth, often up to 25nm. Structural filters can be designed with wider bandwidths as shown in Figure 3. The modeled structure is again based on Ta2O5 waveguides built on fused silica substrates arranged in a resonant cavity configuration. By modifying the configuration of the structural waveguides, the bandwidth of the filter has been increased from a FWHM of 0.4nm in Figure 2, to about 15nm in Figure 3.

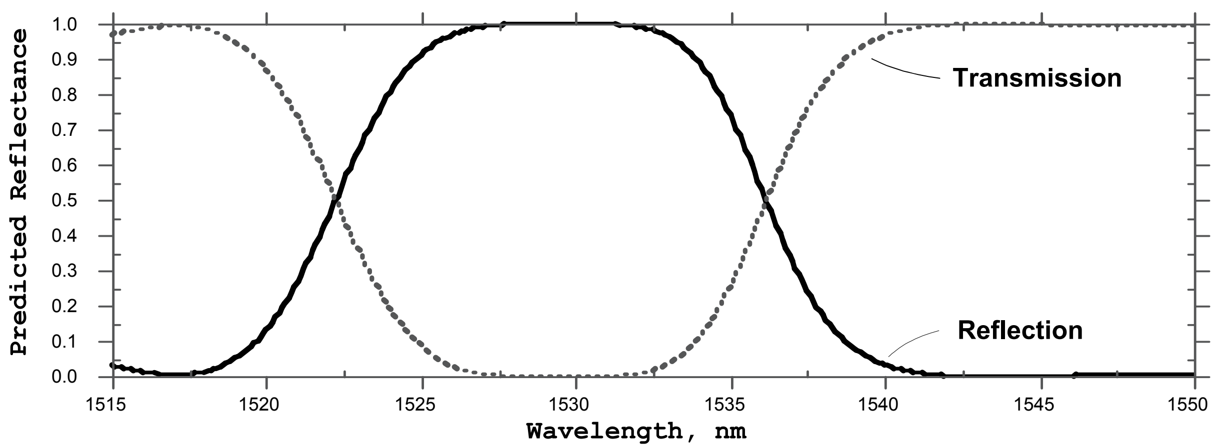


Figure 3: Predicted performance of a 20nm wide NIR surface structure filter configured with a resonant cavity.

Design of Structural Infrared Transmission Filters

A design for a MWIR surface structure transmission filter centered at 3500nm is shown in Figure 4. Cross sectional and overhead views of the design structure are shown. Note that the high degree of circular symmetry in the honeycomb grid pattern provides for polarization independent operation. The structure is built upon an sapphire substrate and is composed of just two materials, aluminum oxide (Al2O3) and germanium (Ge). These materials were chosen for their ruggedness and well-known deposition and etch characteristics. The design of Figure 4 is readily fabricated with just a three step manufacturing process; 1) deposition of the Ge and Al2O3 layers; 2) structure lithography and definition via partial etch of the Al2O3 layer; 3) line of sight deposition of the top Ge layer.

The predicted reflection and transmission of MWIR light through the structure of Figure 4 is shown in Figure 5. A narrow band pass centered at 3500nm is predicted, with a classic single cavity Fabry-Perot profile, and a full-width-half-maximum (FWHM) of 12nm. Isolation over the 3 to 4 micron range is better than 99%. (As previously mentioned, to obtain the equivalent performance with multi-layer thin-film interference coatings would require more than 25 film layers with a total thickness exceeding 8 micron.) Blocking on the short wave side is generally above 99% with the exception of wavelengths below 2500nm, where loss due to diffraction from the structures is anticipated. Diffraction losses are generally eliminated by decreasing the structure pitch, while altering the structure duty cycle to compensate. Blocking on the long wave side can be improved by adding more uniform and structural layers, or with alternative designs. For example, the design shown effectively employs single order layers – one-quarter-wave thickness for the effective index of the structural layers. As found with the evolution of thin-film filter design, the use of multiple order layers can improve the filter shape and out-of-band blocking[15]. In addition, the current model does not include absorption in the sapphire substrate at wavelengths beyond 4 micron. Such absorption would increase the long wave blocking by a factor of 2.

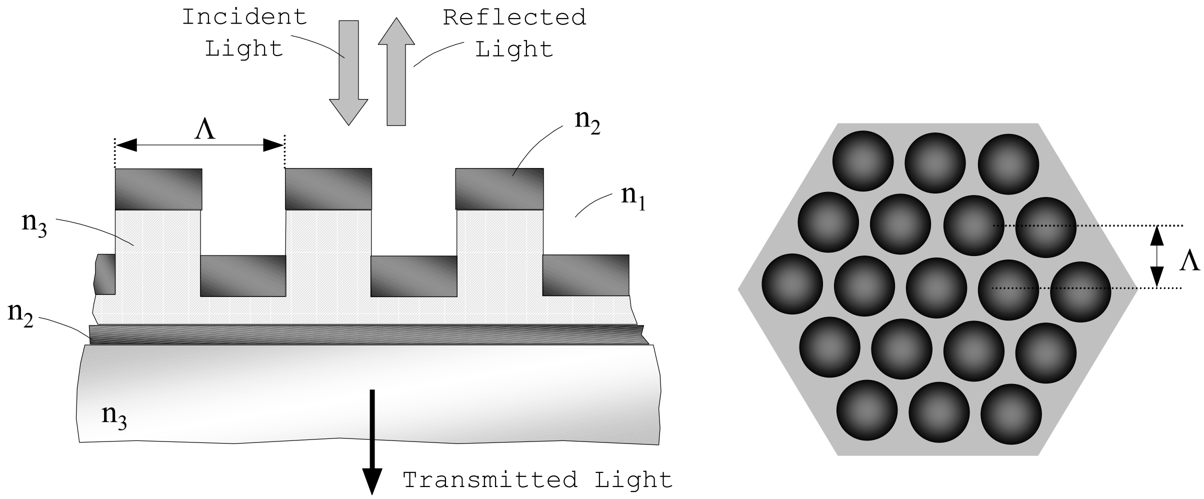


Figure 4: Cross sectional and overhead views showing the design of a narrow-band transmission filter for the MWIR.

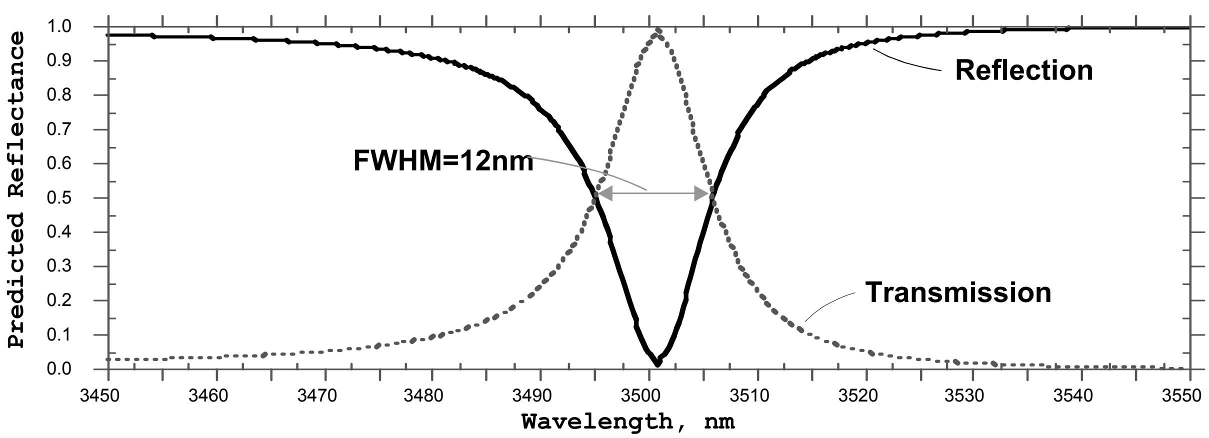


Figure 5: Predicted performance of a MWIR transmission filter modeled as shown in Figure 4.

Figure 6 shows the predicted performance of the band pass filter design shown in Figure 4 when MWIR light is incident at angles off the normal. No structural changes were made to the filter design. As found with thin-film filters, fine-tuning of the filter center wavelength can be performed by mechanically tilting the filter. This provides a significant practical advantage to the fabrication process by reducing the tolerance on precise band positioning. In addition, such angle tuning can be used to tune between communications bands in a laser communications system. Figure 6 shows that angle tuning of just 6 degrees is sufficient to isolate three channels.

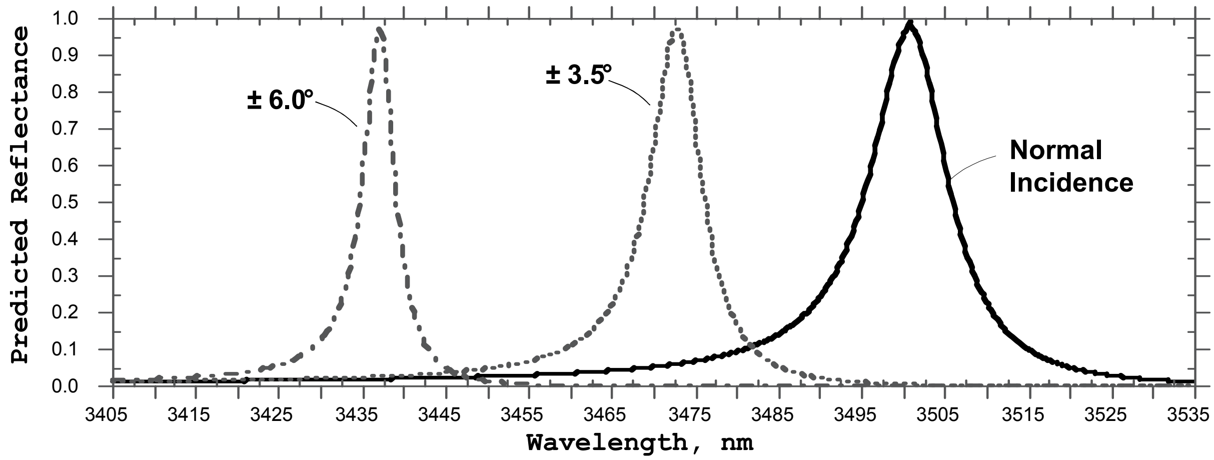


Figure 6: Angle tuning of the MWIR transmission filter modeled as shown in Figure 4.

Design of Structural, Multiple-Notch, LWIR Rejection Filters

Waveguide resonant filter design is readily adapted for devices operating in the LWIR, a region of the IR spectrum where thin-film filter technology becomes impractical due to the film thicknesses required. In addition, LWIR structural filters can be designed to reject multiple narrow-wavelength bands from just a single filter structure. A cross section of a multiple-notch LWIR rejection filter is shown in Figure 7. The design is built upon a clear zinc sulfide (ZnS, multi-spectral grade, ClearTran®) substrate coated with a thin layer of Ge. The Ge layer is covered by a surface structure etched into a top layer of ZnS. The rejection filter operates in air with a pattern pitch of 3 micron. The modeled performance for this design, also shown in Figure 7, predicts that for broad-band illumination, two narrow-wavelength bands, or notches, will be reflected with an efficiency above 99%. The structural waveguide dimensions and materials do not support a free-space propagating diffracted beam within the LWIR band, and with no significant absorption, the performance can be optimized for a reflection loss of less than 3% outside the filter notches. Designs with one, two, or even three rejection bands are possible with this filter configuration.

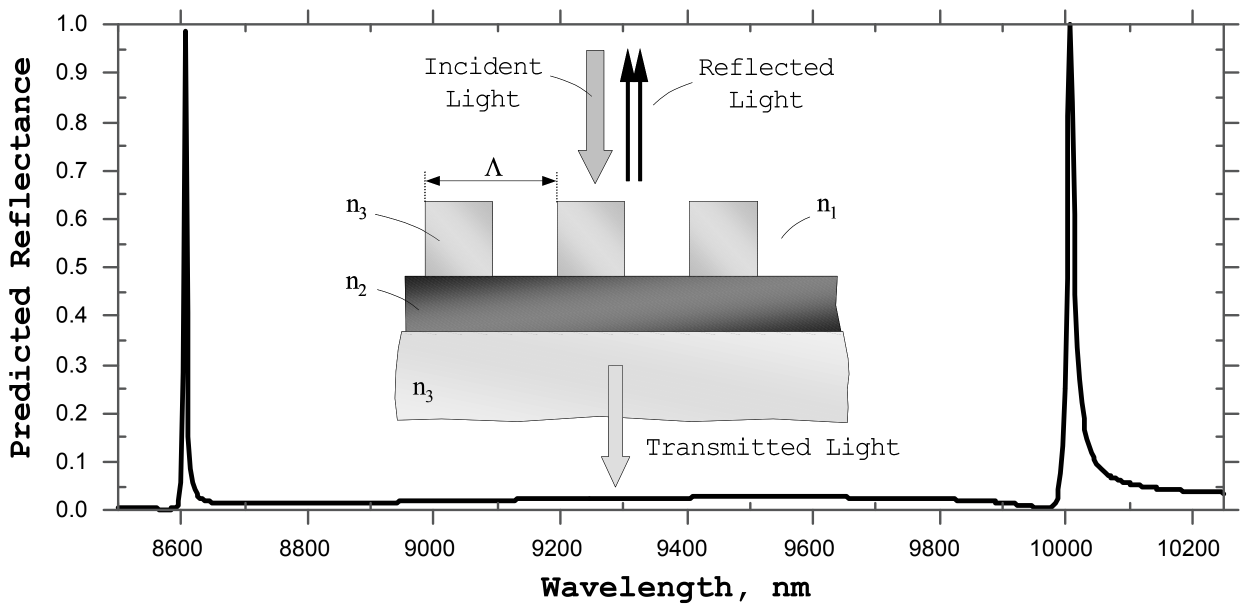


Figure 7: Predicted performance of a LWIR rejection filter.
A cross sectional view of the design for the multiple-notch filter is shown in the inset.

Flexible Positioning of the Notch

Figure 8 shows the predicted transmission of the rejection filter in Figure 7 when the pitch of the structure is varied. No other changes were made to the filter design. Tuning of the filter center wavelength by nearly 2 microns is possible with only a 0.7 micron adjustment to the structure pitch. In addition, very little effect on the filter shape or efficiency is predicted. This flexibility allows a significant cost savings through the use of a common design and fabrication process. As described in the Fabrication Section 4 below, the filter structure pitch is easily varied using our holographic patterning technique[23,24]. Notice that the secondary notch for the hologram pitch of 3440nm falls near the primary notch of the hologram filter design with the 2750nm pitch. By cascading structural filters with varying pattern pitch, multiple narrow band notches can be clustered together to form a comb filter. Comb filters could be used to reject all of the possible wavelengths produced by tunable CO2 lasers.

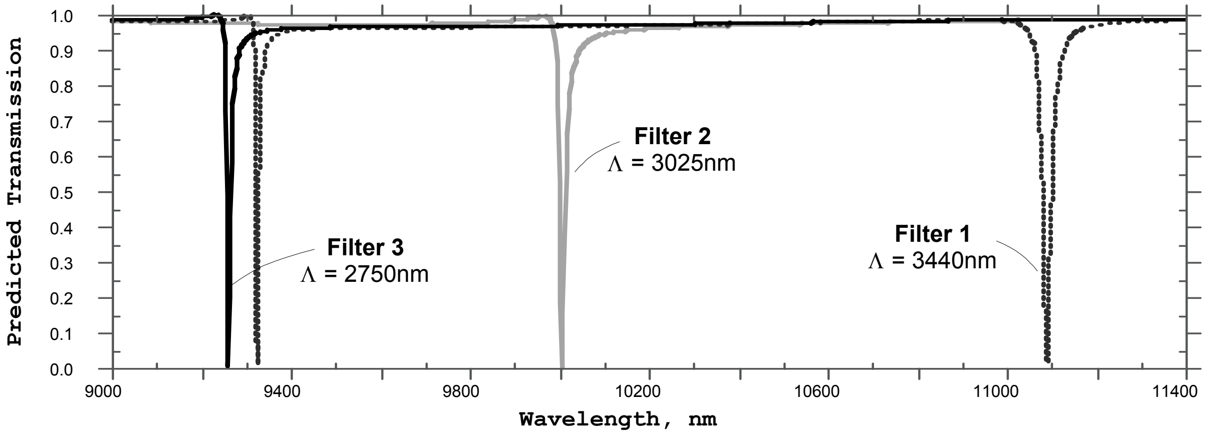


Figure 8: Cascaded multiple-notch LWIR rejection filters forming a comb filter.

Design of Structural Rejection Filters For Operation in the Far Infrared

Using a similar design approach as that shown in Figure 7, we have made a preliminary study into the design of narrow-band filters that operate on light in the very far infrared region from 50 to 2000 microns (FIR). A portion of this region is currently being referred to as the terahertz (THz) band (100 to 300 micron). A brief review of the non-absorbing materials and substrates suitable for the FIR showed that silicon, quartz, and polyethylene are good candidates for the filter substrate. Waveguide layer materials available include germanium, silicon carbide, silicon, and ZnS. Surface structure materials that appear promising are silica (SiO2), yttria, and magnesium fluoride. A filter structure consisting of an array of hexagonal cross section columns within an SiO2 layer deposited on a uniform layer of ZnS, was modeled. The filter structure is supported by a quartz substrate. Figure 9 shows the predicted reflection and transmission through the filter for 3 THz light. A multiple notch rejection filter response is predicted, with a full width half maximum of 150nm (0.4 cm-1). As with the other filter designs described in this section, the rejection bands of the filter can be located anywhere within the THz band by changing the structure pitch. Single or triple-notch rejection filters and transmission filters are also possible.

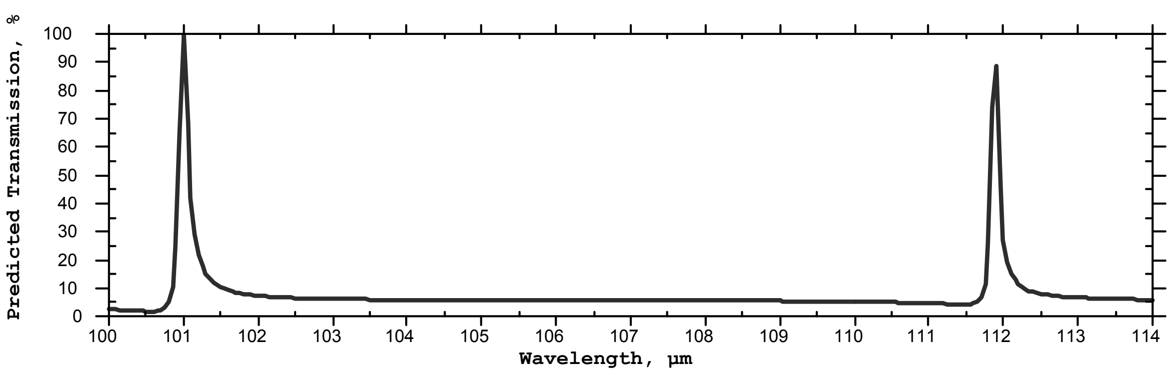


Figure 9: Predicted reflectance of a structural filter designed for the THz band.

4. FABRICATION

Surface relief microstructures needed for waveguide resonant filters, are defined in IR transmitting materials, using batch processing to directly etch the filter structures into the structural layers. Fabrication is a two-stage process where lithography is used to pattern the microstructure, and conventional etching methods are employed to transfer the patterns into the surface of the final product. Figure 10 shows a process flow diagram typical of structural filter fabrication. The process begins with deposition of the waveguide and structural layers onto the filter substrate – typically done by vacuum evaporation (step 2). A conventional positive photoresist material such as one of the AZ1500 series, is then coated onto the filter surface (step 3). Next a non-contact, maskless lithography technique is employed to expose a latent image of the filter texture in the photoresist layer (step 4). The structure lithography is completed by a wet development step that delineates the image as a surface relief texture in the photoresist layer (step 4).

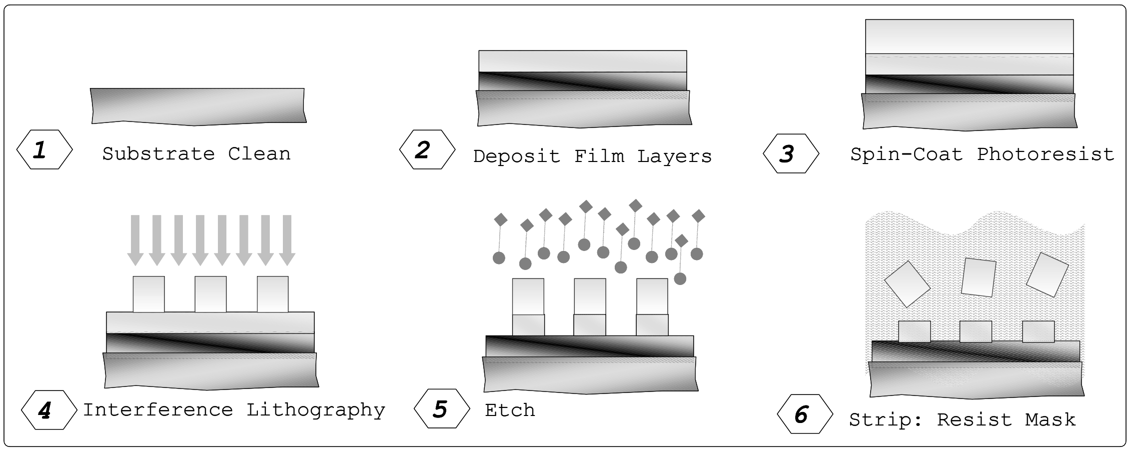
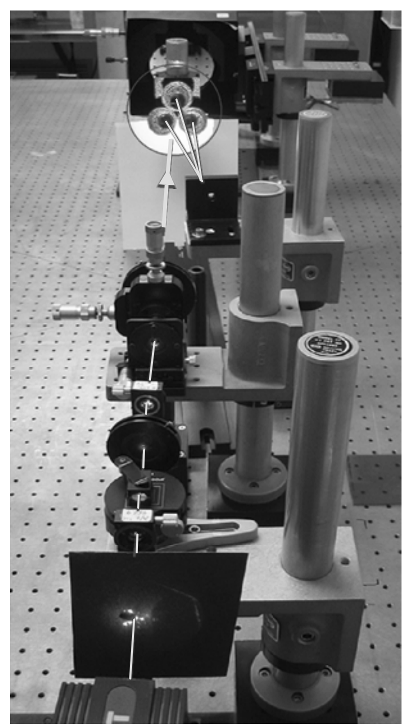


Figure 10: General process flow diagram used in the fabrication of filter microstructures.

A sophisticated patterning method known as interference, or holographic lithography (HL), is used to record the surface structures needed for waveguide filters[23,24]. A bench-top HL tool is shown on the right. Multiple beams of light are split from a laser source (typically emitting in the blue or violet), expanded and redirected to overlap in a region of space where the resulting interference pattern can be recorded. The platform in the middle-upper-right of the photograph is illuminated by three overlapping beams derived from the laser source seen at the bottom of the photograph. An HL system can pattern large field sizes, limited only by the size of the beam that can be created, in a single rapid exposure. Highly uniform structures have been fabricated over 6-inch diameter windows. A significant advantage to HL patterning is the very large depth of field, on the order of inches, which eliminates image focus problems that spherical optics present to conventional lithography equipment such as image projection steppers and contact mask aligners. Figure 11 shows multiple SEM images of micro-structures recorded in photoresist using an HL system. From left to right, profile, elevation, and overhead views are shown of both post-type structures and hole-type structures intended as masks in the fabrication of LWIR multiple-notch rejection filters. In the SEM images of the hole-type mask structure, both ZnS and Ge filter layers can be seen underneath the resist mask. The structures have a pattern pitch of 3450nm and a height of about 4000nm in the case of the post-type structures, and a pattern pitch of 2900nm and a height of about 2500nm in the case of the hole-type structures. A ClearTran® window supports the structures.



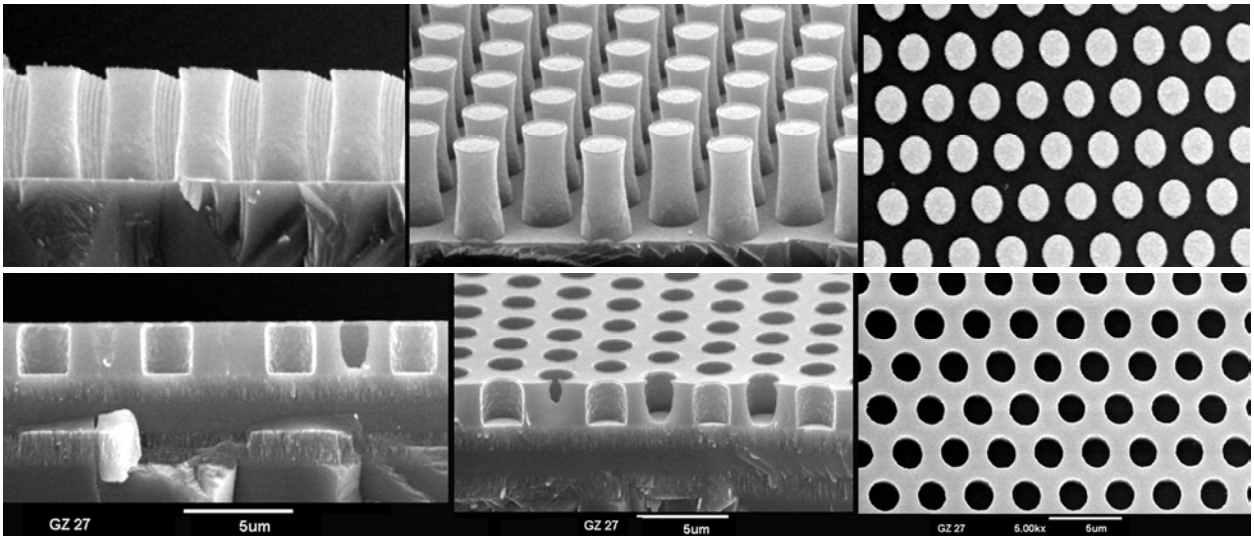


Figure 11: SEM micrographs showing profile, elevation, and overhead views of hole(lower) and post(upper) structure photoresist masks on prototype LWIR filter layers prior to pattern transfer via etching.

Once the filter texture has been recorded in the photoresist mask layer, the mask is used to transfer the resist texture into the structural layer using standard dry etching techniques (step 5) such as ion bbeam milling and reactive ion etching. If required, removal of the residual photoresist mask material completes the process (step 6). A thorough understanding of the interaction between lithography and etching is essential to fabricating filter structures, as the finished etched structure will be different than the starting resist profile. This is because the physical and chemical aspects of etching are quite variable for different materials, and process development must compensate.

5. CHARACTERIZATION

Surface structure filters are characterized using SEM analysis, FTIR transmission measurements, and both transmission and reflectance measurements in the NIR using an Agilent optical spectrum analyzer and a grating-based spectrometer. In addition, precise microstructure pitch and symmetry are configured using diffraction measurements obtained with a fiber-coupled white light spectrometer arranged in the Littrow configuration. Data collected for fabricated structural filters is presented next.

6. MEASURED FILTER PERFORMANCE

6.1 Surface Structure Rejection Filter for 780nm - NIR

Using the fabrication techniques just described, prototype surface structure filters designed for narrow-band reflection at 780nm in the NIR, were built. One prototype was fabricated as an array of holes in a silicon nitride (Si3N4) layer deposited onto a glass substrate (Schott Borofloat glass, n=1.48). The hole-array had a hexagonal grid configuration consisting of 250nm diameter holes etched all the way through the 190nm thick layer of Si3N4 (n~1.85). This first filter functioned nearly as designed except for the unexpected loss due to absorption in the Si3N4 layer. A second prototype was built using a zinc sulfide (ZnS) layer which has consistently low absorption regardless of the technique used for deposition. A post, or mesa-type structure was fabricated in a ZnS layer deposited on a glass substrate. Figure 12 shows SEM micrographs with both elevation and overhead views of the ZnS layer structure. Notice the high level of circular symmetry afforded by the hexagonal grid configuration. This symmetry allows the device to function in an identical fashion without regard to the polarization state of the illuminating light, and without regard to the position at which the illuminating light strikes the array. This polarization independent operation is an important advantage in the chemical sensing application for which the filter was designed. It is also a critical requirement of filters operating on telecommunications signals.

The structure shown in Figure 12 consists of isolated, approximately 300nm diameter mesas, 170nm high, spaced on a 520nm triangular grid.

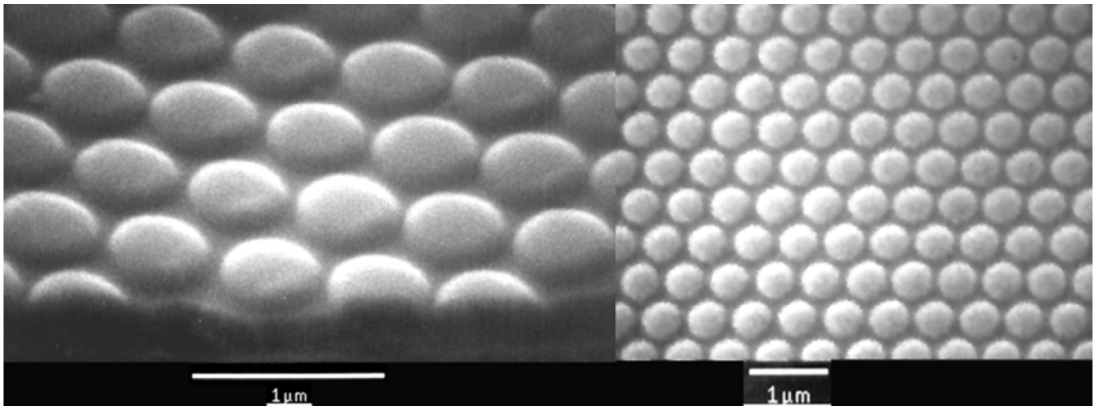


Figure 12: SEM images showing elevation and overhead views of a 780nm surface structure rejection filter.

Figure 13 shows the measured reflection from the ZnS filter structure for NIR light incident normal to the filter window. The solid line in the plot is the measured data showing nearly lossless performance – over 95% reflection centered at 777nm. The dashed curve in the figure shows the predicted performance of the filter taking into account the fabrication errors. Note that agreement between measured and modeled reflection is quite good.

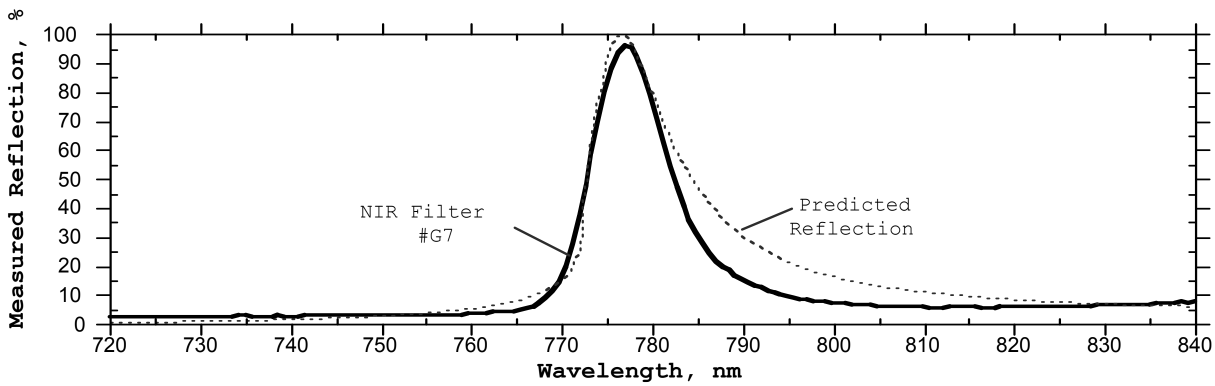


Figure 13: Measured reflectance of a 780nm surface structure rejection filter compared to the modeled reflection.

A variation on the ZnS filter design shown in Figures 12 and 13, can produced multiple narrow-band reflections from a single surface structure. A third prototype was constructed again using ZnS as the structural layer. With this design the mesa structure thickness is adjusted and the structure height is set to maintain a thickness of ZnS with no structure. The result is a triple-notch rejection filter as shown in the measured reflection curve shown in Figure 14. Again a primary notch at 777nm is observed, but two additional notches at 885nm and 920nm are present.

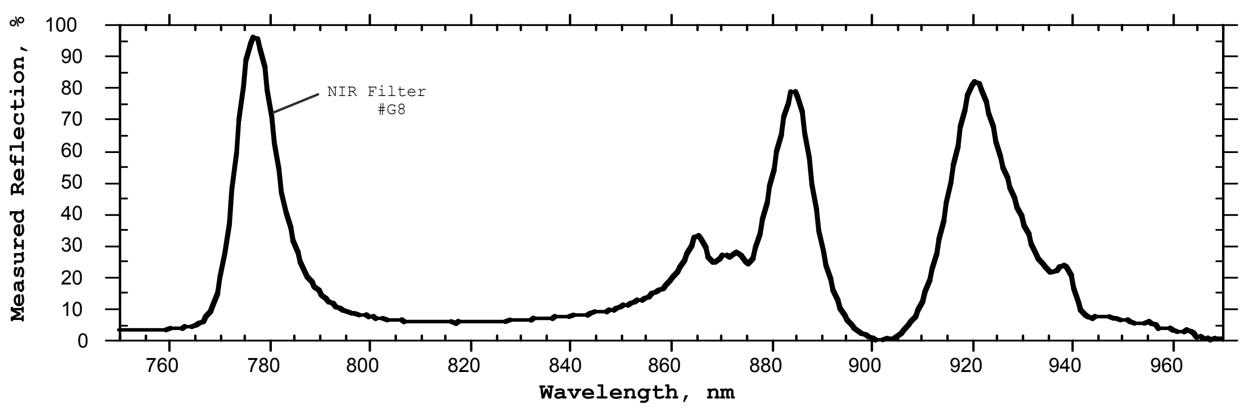


Figure 14: Measured reflectance of a triple-notch surface structure rejection filter.

6.2 Surface Structure Rejection Filter for 1550nm - NIR

Figure 15 shows SEM images of a surface structure filter designed for use at telecommunications wavelengths in the NIR. Edge, elevation, and overhead views are shown. The design for the structure called for a structured layer of aluminum oxide (Al2O3, n=1.65) over a uniform waveguide layer of Ta2O5. For convenience in proving the filter design, a patterned layer of non-absorbing photoresist (n=1.65) was used in place of the Al2O3 layer. Again a hexagonal array of holes was fabricated, but with a grid spacing of 975nm to shift the resonance out to the telecommunications band centered at 1545nm.

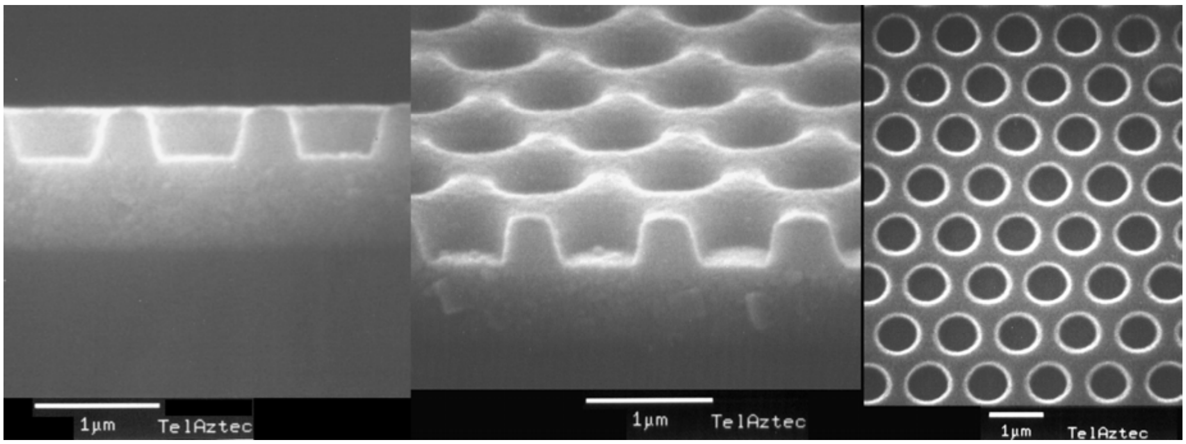


Figure 15: SEM images of a hole-type 1550nm surface structure rejection filter designed with a uniform waveguide layer.

Figure 16 shows the measured reflection from the filter structure shown in Figure 15, again for NIR light incident normal to the filter window. The solid line in the plot is the measured data showing nearly lossless performance – over 95% reflection centered at 1533nm. The dashed curve in the figure shows the predicted performance of the filter taking into account the fabrication errors, and shifted slightly to separate it from the measured data. Note that agreement between measured and modeled reflection is again quite good.

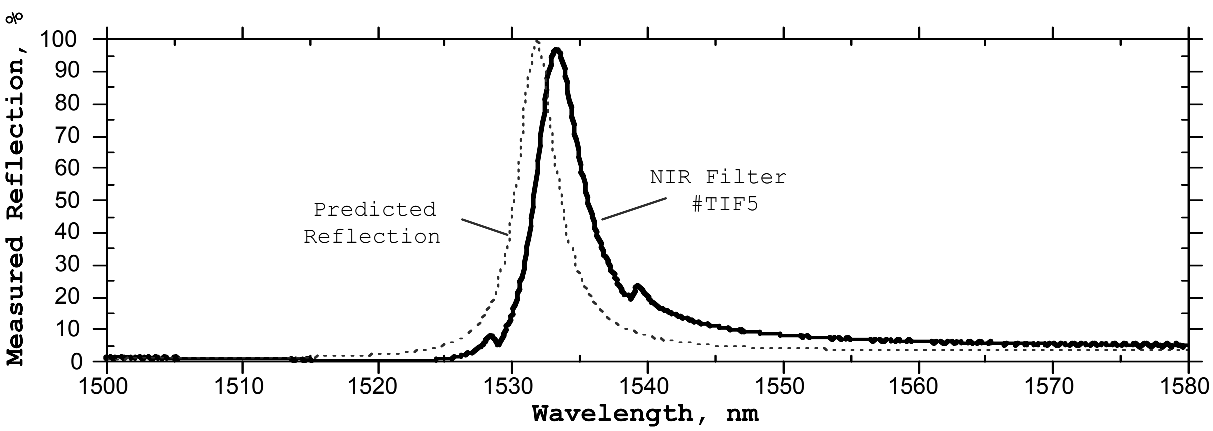


Figure 16: Measured vs. predicted reflectance of a 1535nm surface structure rejection filter.

Figure 17 shows another NIR structural filter prototype intended as part of an electro-optic tunable filter. The design is based on a structural waveguide consisting of holes in an Al2O3 layer deposited on fused silica (n=1.45). Two filter structures are used in a resonant cavity configuration, where the cavity is filled with an electro-optic material such as liquid crystal. Again for ease in proving a design concept, photoresist is used in place of the Al2O3 layer. Figure 17 shows the photoresist structure supported by a fused silica substrate prior to assembly of a resonant-cavity filter. Figure 18 shows the measured reflectance from the complete structural filter assembly with xylenes (n=1.51) filling the resonant cavity. Note that a logarithmic scale is shown to better illustrate the filter performance. A widened, or flat-top pass-band is observed which is consistent with the resonant cavity design. The resonant cavity design also increases the slope of the band edges, providing for the needed channel separation in a telecommunications system. The isolation of the filter band is also quite high – better than –27dB over the entire telecommunications C-band (1520 to 1570nm). The overall loss of the device is high due to absorption in the xylenes material.

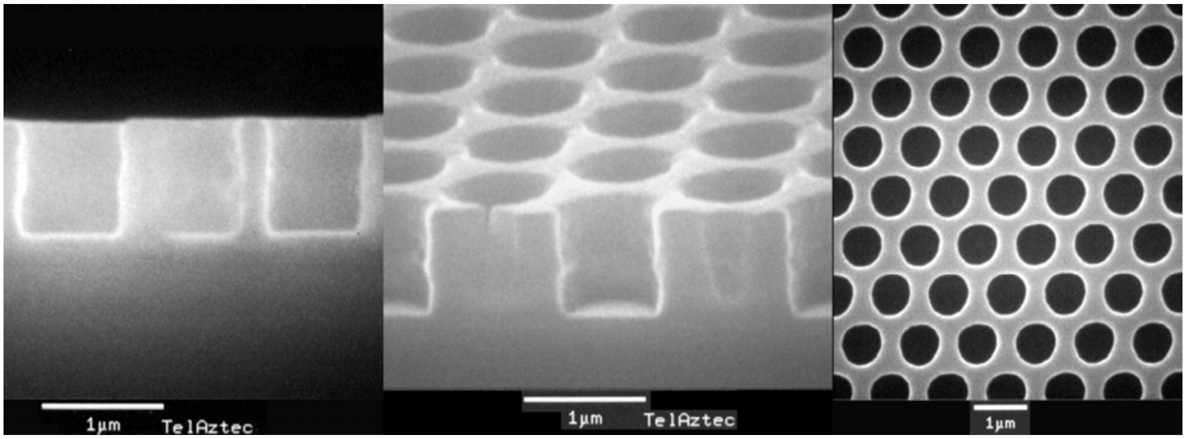


Figure 17: SEM images of a hole-type 1550nm surface structure rejection filter intended for a resonant cavity prototype.

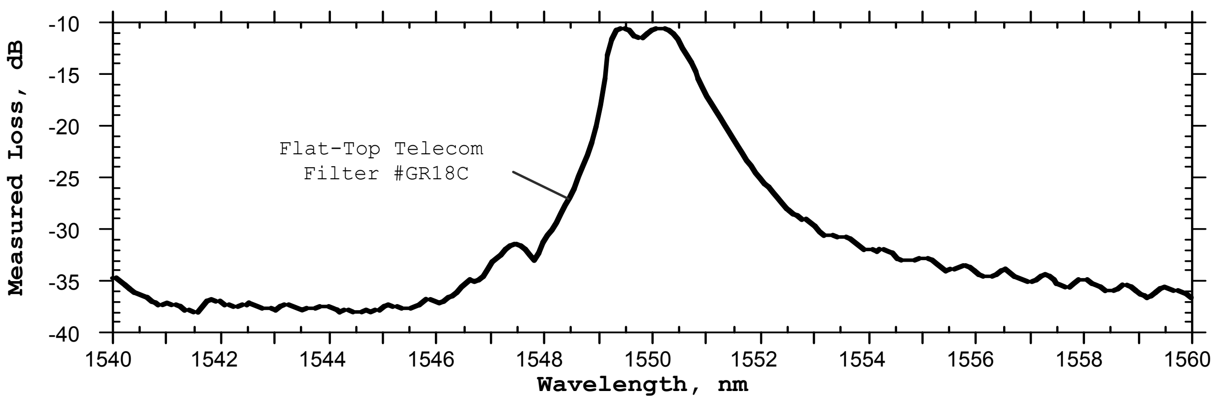


Figure 18: Measured reflectance of a 1550nm resonant-cavity-type surface structure rejection filter.

6.3 Multiple-Notch Surface Structure Rejection Filter for 10 micron - LWIR

Figure 19 shows two sets of SEM images of prototype LWIR rejection filters. The top row of images is of a post-type structure fabricated in a ZnS layer. A uniform waveguide layer of Ge is employed under the structural ZnS layer, and the entire filter design is supported by a ClearTran® substrate. The same material layers are shown in the lower row of hole-type LWIR filter prototypes. This filter structure is designed to reject two narrow-band wavelength regions out of the broad LWIR spectrum, and to transmit all other wavelengths with high efficiency.

Figure 20 shows the measured transmission through a hole-type LWIR filter prototype like that shown in the lower images of Figure 19. (No anti-reflection treatment was used on the surface of the ClearTran® window opposite the filter structures. This leads to a maximum transmission of about 85 to 86% as shown by the solid grey curve in the figure). The solid black line shows the measured transmission, and the dashed line shows the predicted transmission that in this case was not adjusted to match the errors in fabrication. Two notches in the measured transmission are observed with a separation of about 1.3 micron, in good agreement with the predicted separation. The notch minimum falls below the 8% level for the short wave notch, indicating a rejection efficiency of about 77%. Higher efficiency is expected as the fabrication process is refined. The notch width is also quite large compared with the predicted width. The diameter and profile of the hole-structures has the dominant effect on notch width, and tolerance for error in the fabrication of the hole structures is quite low for this multiple-notch design. Lastly, the out-of-band transmission falls below the maximum predicted. Again the thickness of the structural and uniform waveguide layers, and the hole diameter and profile, have a strong impact on the anti-reflecting properties of the filter, and must be precisely controlled.

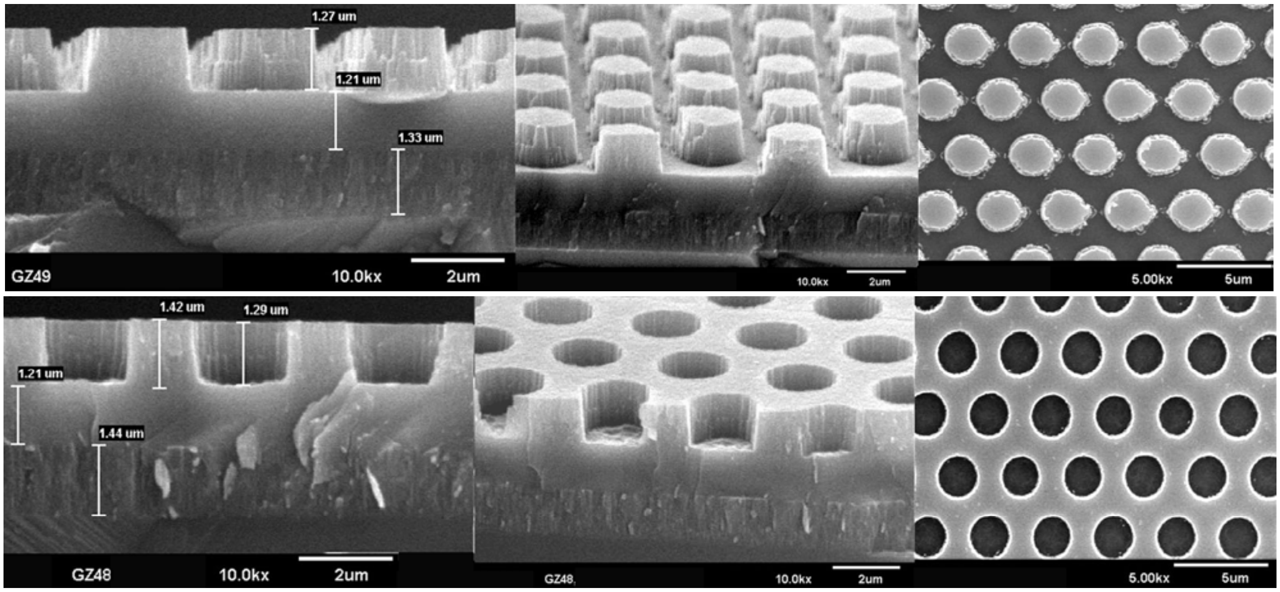


Figure 19: SEM images of prototype multiple-notch surface structure rejection filters designed for the LWIR. Post-type structures are shown in the upper row of images and hole-type structures are shown in the lower set of images.

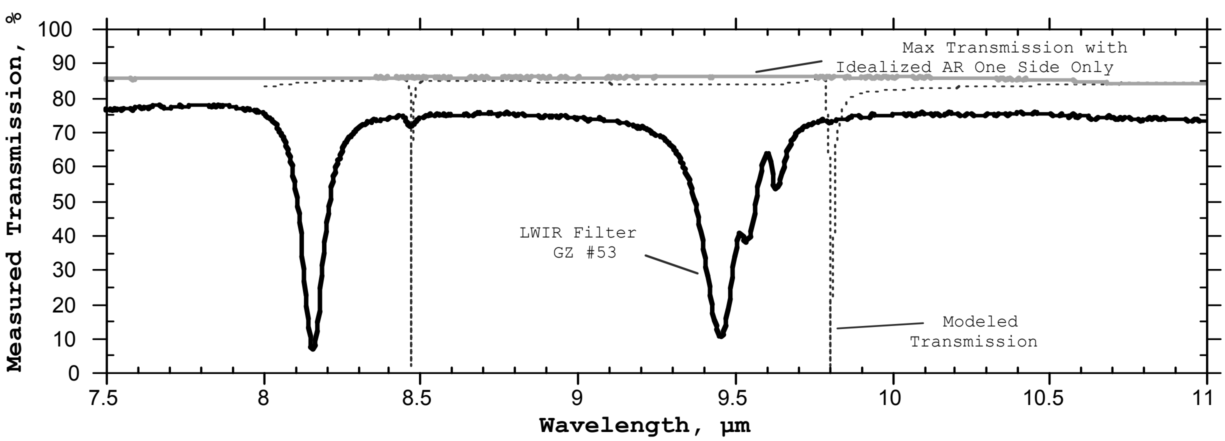


Figure 20: Measured vs. predicted transmission through a hole-type double-notch LWIR structural filter.

Figure 21 shows the measured transmission through a post-type LWIR filter prototype. Very high rejection efficiency is observed with high out-of-band transmission. The notch positions agree well with the predicted notch locations indicated by the dashed curve in the plot. With this prototype, the notch width is very much larger than predicted, due again to fabrication errors in the shape of the surface structures, and to structure uniformity. The additional structure observed on the transmission notches indicates errors in the symmetry of the structure array spacing.

A first attempt at producing a triple-notch filter was made employing the same ZnS and Ge materials. Figure 22 shows the measured transmission through a hole-type filter prototype – again as the solid black curve. Three notches are shown with a notch separation of about 1.1 micron for the short- and mid-wave notches, and about 1.7 micron for the mid- and long-wave notches. This agrees well with the predicted transmission as shown by the dashed curve. While this data demonstrates that triple-notch LWIR filters are feasible, the tolerances on manufacturing may be too low to produce a practical device with this design. Alternative designs are under investigation.

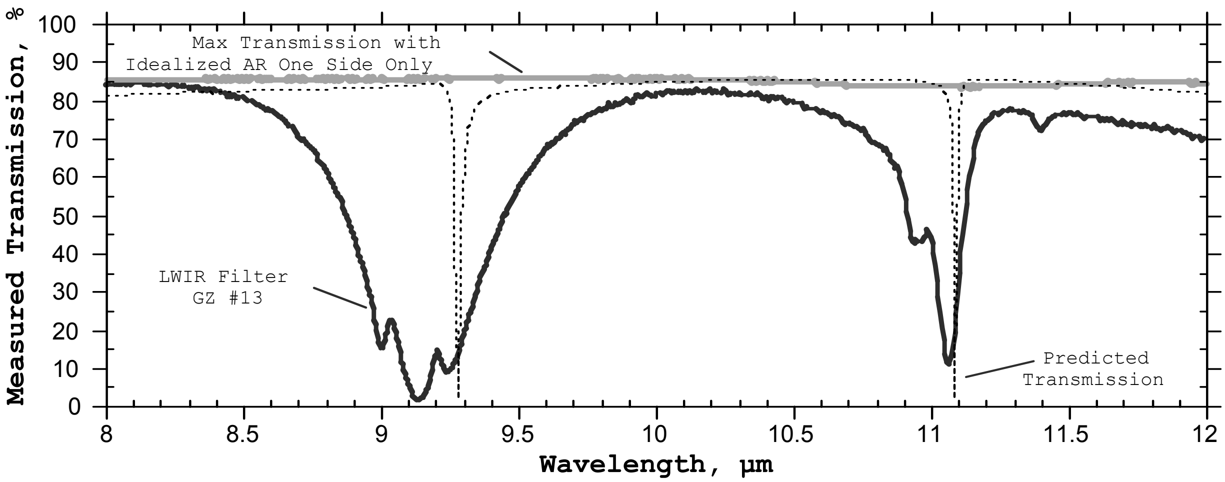


Figure 21: Measured vs. predicted transmission through a post-type double-notch LWIR structural filter.

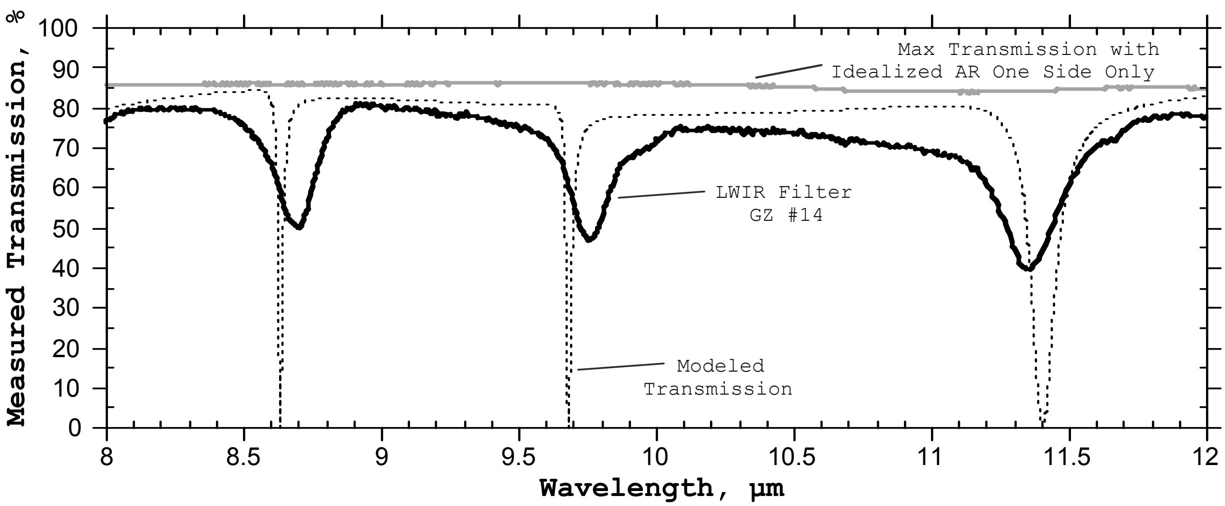


Figure 22: Measured vs. predicted transmission of a triple-notch surface structure rejection filter for the LWIR.

7. SUMMARY

Surface structure narrow-band transmission or rejection filters can provide high performance and unique multiple-band functionality in a rugged package. Large area filter windows can be fabricated without the cost penalty typical of thin-film filter technology. The practical design of surface structure waveguide resonant filters has been discussed for a variety of important infrared applications. Interference lithography is used to pattern the repetitive structures because of the large field size, large depth of focus, and high process throughput characteristics of the technique. Filter prototypes were fabricated in materials used throughout the infrared spectrum. SEM images of the filter structures are shown, and transmission data is presented, with experimental results matching the predicted performance.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] The University of Reading Infrared Multilayer Laboratory, (www.cyber.rdg.ac.uk/irfilters/), page 3 of HIRDLS presentation
[2] II-VI Company technical information – Germanium (www.ii-vi.com),
[3] Janos company website – www.janostech.com
[4] Raguin, D.H. and Morris, G.M., "Structured surfaces mimic coating performance", Laser Focus World, April 1997, pgs 113-117
[5] Mashev, L. And Popov, E., "Zero Order Anomaly of Dielectric Coated Gratings", Optics Communications, Vol. 55, No. 6, 15 October 1985, pg. 377
[6] Mazuruk, K., "Bragg diffraction in the vicinity of Woods anomalies", J. Opt. Soc. Am. A, Vol. 7., No. 8, August 1990, pg. 1464
[7] Wang, S.S., Magnusson, R., Bagby, J.S., and Moharam, M.G., "Guided-mode resonances in planar dielectric-layer diffraction gratings", J. Opt. Soc. Am. A, Vol. 7., No. 8, August 1990, pg. 1470
[8] Magnusson, R. and Wang, S.S., "New principle for optical filters", Appl.Phys.Lett., 61(9), 31August1992, 1022
[9] Wang, S.S., and Magnusson, R. "Theory and applications of guided-mode resonance filters", Applied Optics, Vol. 32, No. 14, 10 May 1993, pg 2606
[10] Wang, S.S., and Magnusson, R. "Design of waveguide-grating filters with symmetrical line shapes and low sidebands", Optics Letters, Vol. 19, No. 12, June 15, 1994, pg 919
[11] Peng, S. And Morris, M., "Experimental demonstration of resonant anomalies in diffraction from two-dimensional gratings", Optics Letters, Vol. 21, No. 8, 15 April 1996, pg 549
[12] Peng, S. And Morris, M., "Resonant Scattering from two-dimensional gratings", J. Opt. Soc. Am. A, Vol. 13, No. 5, May 1996, pg. 993
[13] Sharon, A., et. al. "Resonant grating-waveguide structures for visible and near infrared radiation", J. Opt. Soc. Am. A, Vol. 14, No. 11, Nov. 1997, pg. 2985
[14] Brundrett, D., et. al., "Normal-incidence guided-mode resonant grating filters: design and experimental demonstration", Optics Letters, Vol. 23, No. 9, May 1, 1998, pg.700
[15] MacLeod, H.A., Thin Film Optical Filters,Third Edition,Institute of Physics Publishing,Bristol,Philadelphia, 2001
[16] Tibuleac, S., and Magnusson, R., "Reflection and Transmission Guided-mode Resonance Filters", J. Opt. Soc. Am. A, Vol. 14, No. 7, July 1997, pg 1617
[17] Priambodo, P.S., Maldonado, T.A., and Magnusson, R., "Fabrication and Characterization of High-Quality Waveguide-mode Resonant Optical Filters",Applied Physics Letters, Vol.83(16) October 20,2003, pp 3248-3250.
[18] Magnusson, R., and Wang, S.S., "Transmission band-pass guided-mode resonance filters", Applied Optics, Vol. 34, 1995, pg 8106
[19] Magnusson, R., et.al., "Efficient Band-pass Reflection and Transmission Filters With Low Sidebands Based on Guided-Mode Resonance Effects", U.S. Patent 5,598,300 issued January 28, 1997.
[20] Cowan, J.J., "Aztec surface relief volume diffractive structure", J. Opt. Soc. Am. A., 7, No. 8, August 1990, pgs 1529-1544
[21] Hobbs, D.S. and Cowan, J. J., "Optical Device For Filtering and Sensing", U.S. Patent 6,791,757, Sept. 14, 2004.
[22] Cowan, J. J., "Electro-Optic Device Allowing Wavelength Tuning", U.S. Patent 6,707,518, Mar. 16, 2004.
[23] Hobbs, D.S., et. al., "Automated Interference Lithography Systems for Generation of Sub-Micron Feature Size Patterns", SPIE Conference on Micromachine Technology for Diffractive and Holographic Optics, Proc. SPIE, Vol. 3879, September 1999, pg 124-136
[24] Cowan, J.J., U.S. Patent 4,496,216, "Method and Apparatus for Exposing Photosensitive Material", Jan. 29, 1985.