Cooled optical filters for Q-band infrared astronomy (15-40 µm)

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ABSTRACT

With a growing interest in mid- and far-infrared astronomy using cooled imaging and spectrometer instruments in high-altitude observatories and spaceflight telescopes, it is becoming increasingly important to characterise and assess the spectral performance of cooled multilayer filters across the *Q*-band atmospheric window. This region contains spectral features emitted by many astrophysical phenomena and objects fundamental to circumstellar and planetary formation theories. However extending interference filtering to isolate radiation at progressively longer wavelengths and improve photometric accuracy is an area of ongoing and challenging thin-film research. We have successfully fabricated cooled bandpass and edge filters with high durability for operation across the 15-30 μm *Q*-band region. In this paper we describe the rationale for selection of optical materials and properties of fabricated thin-film coatings for this region, together with FTIR spectral measurements and assessment of environmental durability.

Keywords: Infrared, Thin-Film, Deposition, Optical, Filters, Spectral, Bandpass, Coatings.

1. INTRODUCTION

The last decade has seen many rapid advances in the technological design and sensitivity of cooled infrared optical instruments, with capabilities to observe deeper and with higher clarity the fine detail of countless astrophysical phenomena. The combined measurement capabilities of high-altitude ground-based and space-based telescopes, together with the increased growth in remote-sensing satellites, are making it possible to conduct observations and measurements throughout the entire infrared spectrum. The projected launch and performance envisaged from the cooled thermal-infrared imager and spectrometer on the JWST-MIRI [1] instrument at 7K, together with future prospective next generation [2] telescopes, will target observations that focus on many of these fundamental phenomena of star and planetary formation.

The successful infrared observations originating from many telescope instruments that operate in the *Q*-band region (ESO–VISIR[3], -TIMMI2[4], GTC-CanariCam[5], Subaru-COMICS [6], W.M. Keck-LWS [7], Gemini-TEXES [8], TIRGO-Tircam[9]) has demonstrated the importance and effectiveness of far-infrared filtering across a wide variety of areas in astronomy. The *Q*-band region is rich in absorption features that contain fundamental data on the structure and composition of low-temperature emission sources. This infrared region contains many features from astrophysical objects, the measurements of which determine the temperature, abundance of minerals, chemical composition, and grain size distribution from circumstellar dust and gas disks which are crucial to theories on the formation of planetary systems. Some of the key atomic and molecular absorption lines are located in this region at 24.5, 26.0 μm [Fe II], 25.3 μm [S I], 25.9 μm [O IV] and 28.2 μm [H_2 0-0 S(0)], together with many silicate dust and neutral gas features throughout the 15-40 μm range, some of which are heated by stellar radiation and re-emit at longer *Q*-band wavelengths [10]. Star formation and evolution of galaxies often occur in heavily dust obscured regions, where mid- to far-infrared measurements provide the best means of observation.

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Infrared measurements in the 15-40 μm *Q*-band region are also of importance for observing the thermal emission spectrum of the Earth and other planetary bodies that regulates climate [11]. The climate of the Earth, as seen from space is governed by the radiation balance between incoming solar short-wave energy and outgoing thermal long-wave emission. Direct infrared measurements by remote sensing of planetary temperatures, dust, water vapour and condensates provide an understanding of the planetary state and abundance of atmospheric constituents. These observations subsequently offer an insight into the thermodynamic processes responsible for the structure of the atmosphere and temperature of the planet. This spectral region can also be used to characterise cloud formation [12] , retrieval of atmospheric composition in the presence of ice clouds and planetary thermal energy balance [13].

The desire to extend the range of optical interference filtering to isolate and separate wavelengths in the *Q*-band region is an area of ongoing and challenging thin-film research, with goals to achieve high spectral positioning accuracy, environmental durability and aging stability at cryogenic temperatures whilst maximising high transparency throughput. It is important for infrared optics to be cooled to progressively lower temperatures to reduce noise, improve measurement sensitivity and avoid overwhelming signals originating from low energy sources by suppressing the self-emitting heat sources within the telescope and instrument. Infrared optics must also be capable of withstanding repetitive cryogenic cycling without deterioration. Although the low temperature operation may impose design constraints on the choice of materials, it also provides opportunities to exploit the reduced multiphonon lattice absorption intensity that accompanies the cooling process. In practice however, the design and fabrication of relatively thick thin-film multilayers is difficult due to the limited range of refraction indices and absorption inherent in many infrared materials.

The spectral design and construction of interference multilayers for *Q*-band wavelengths has been notoriously difficult for many years. The small selection of transparent robust materials, together with the prerequisite thick multilayer film thicknesses restricts the ability to achieve both high spectral performance and mechanical durability simultaneously. The realisation of these coatings are constrained by a wide range of design and fabrication limits, of which most notable are; (i) progressively increasing layer count, high layer thickness and associated manufacturing operations, (ii) increasing lattice and/or free-carrier absorption in the composition of deposited layer materials, and (iii) physical quality of microcrystal structure, stress and surface topology of deposited layers. The thin-film designer is subsequently seeking to minimise the amount of deposited material throughout each separate and accumulating multilayer stack. The combination of minimising the layer count and number of stacks to realize the filter specification, together with the process of achieving compromises between high passband transparency, continuous out-of-band blocking intensity and stress-free environmental stability is a demanding requirement that is difficult to resolve other than by experimental processing. The technical difficulties in achieving these performance requirements have hindered FIR spectral measurements by low sensitivity and poor spatial resolution compared to other wavelength ranges, even with the latest improvements in detector sensitivity across the infrared waveband.

Substrate and film materials exhibiting transparency across the *Q*-band range utilise heavy molecular compounds with low lattice absorption properties, these include the alkali-halides, thallium-based mixed halides, Group II-VI dielectric compounds and Group IV elements. Many of the halide materials can possess a variety of undesired properties comprising high stress, susceptibility to long-term exposure to moisture, colour centres and toxicity that limit their usefulness. Deposition of cadmium-based dielectrics and lead (Pb) chalcogenide thin-films on cadmium telluride, silicon, germanium and diamond substrates, while not of outstandingly high mechanical strength have been fabricated and cooled by us, whilst maintaining good transparency performance and durability at wavelengths across the 25-40 μm range. Further, we have fabricated narrow bandpass filters for the 25 μm region that exhibit temperature-invariant properties with negligible wavelength shift on cooling. The unique negative temperature coefficient ($dn/dT<0$) of Pb-based chalcogenide salts, in combination with the positive temperature coefficient of II-VI wideband dielectric materials enable multi-cavity narrow bandpass filters to be designed with exclusive immunity to wavelength shifts with temperature, as described in Section 5.

At 25-40 µm *Q*-band wavelengths, cooled inductive and capacitive thin metal-mesh filters have been investigated and developed in recent years by Sako *et al* [14] with supporting polypropylene and polyimide dielectric substrates. In these filters, dimensional periodicity of orthogonal mesh patterns are designed with prescribed geometry and scale to produce resonance peaks at a desired wavelength, and are unaffected by the material absorption properties in optical interference filters. Mesh filters have been designed with narrow bandpass widths and high transmission, but are inherently subject to short-wave leakage. This can be partially improved by stacking identical mesh filters together incoherently, but some consequential loss of in-band transparency is inevitable. Resonant bandpass peaks have also been recently developed for low temperature operation across the 20-60 µm region by Merrell *et al* [15], using semiconductor micromachining processes to fabricate compact, free-standing metal-mesh filter arrays with silicon support frames, and Wada *et al* [16] who have developed mono-material sub-wavelength structures, all of which also exhibit some degree of short wavelength leakage.

2. SUBSTRATE MATERIAL PROPERTIES

In this paper we report on properties of infrared coatings deposited on CdTe, Si, Ge and Diamond substrate materials. Although there is also a sustained interest in the use of alkali-halides (e.g. NaCl, KCl, KBr, CsI etc.) and thallium-based mixed halide compositions (e.g. KRS-5, KRS-6) as window materials, coatings designed and deposited for these substrates have good optical performance at room temperature, but frequently result in fracture due to thermal expansion disparity at the multilayer and substrate interface with moderate cooling (<250 K) [17]. For example, the linear thermal expansion coefficients of these halides are exceptionally high (KRS-5 $\alpha_L \cong 58\text{x}10^{-6}$/°C, CsI $\alpha_L \cong 50\text{x}10^{-6}$/°C) compared with most chalcogenides ($<10\text{x}10^{-6}$/°C). Suitable matching of material combinations with graded thermal expansion and refractive index contrast is limited, which together with the cumulative toxicity of thallium-based materials precludes many investigations in this area.

Chemical vapour deposited Cadmium Telluride (CdTe) is now processed as a fully characterised and mature substrate material, suitable to provide high transparency throughout the mid-infrared region to wavelengths around 30 µm at 20K (Fig. 1). It is known to be fragile with a cubic crystal structure which is easily prone to surface scratching, chipping and cleavage if exposed to mechanical strain, however as a practical optical substrate material it is effective for cryogenic operations where low thermal expansion is desired [18]. In addition to the spectral and physical properties, CdTe can be optically worked with high metrology precision and surface quality performance. Typical surface flatness and parallelism values are achieved with transmitted wavefront error (WFE) of λ/10 P-V at 20 µm, and < 30 arcsec wedge angle across a 25 mm diameter aperture [19]. Careful consideration to equalise multilayer thickness disposition between surfaces is however crucial to minimise flatness deviations that may result from differential coating stress.

Silicon and germanium semiconductors are probably the most well-known and understood materials for applications in solid-state devices. As thin optical substrate materials (<0.5 mm), they also retain considerable promise of transparency for wavelengths in the >20 µm region when cooled (Figs. 2, 3). Wide bandpass coatings have been deposited on thin Ge substrate materials in the 20-25 µm region with good optical and durable performance at temperatures between 295-20K. However, to exploit the full transparency bandwidth of silicon across the FIR (> 20 µm) region is problematic, often resulting in adhesion failure on cooling due to its low thermal expansion coefficient [20] $\alpha_L = 2.6\text{x}10^{-6}\ K^{-1}$, compared to 6.1 $\text{x}10^{-6}\ K^{-1}$ for Ge, 6.5 $\text{x}10^{-6}\ K^{-1}$ for ZnS, 7.1 $\text{x}10^{-6}\ K^{-1}$ for ZnSe, 5.9 $\text{x}10^{-6}\ K^{-1}$ for CdTe, and 9.0 $\text{x}10^{-6}\ K^{-1}$ for PbTe . Long-wave pass edge filters fabricated on silicon capable of providing transparency across the *Q*-band region often fail due to compressive stress at temperatures below 150K.

The exceptional combination of mechanical, thermal, chemical and optical properties of cooled CVD diamond has also long been recognised as an extremely attractive potential *Q*-band substrate material, offering continuous broadband transparency for FIR filtering. Figure 4 shows the transmission spectrum of a 0.7 mm thick uncoated substrate cooling from 295K to 20K. Prototype coating depositions for prospective *Q*-band filters are described in Section 6.

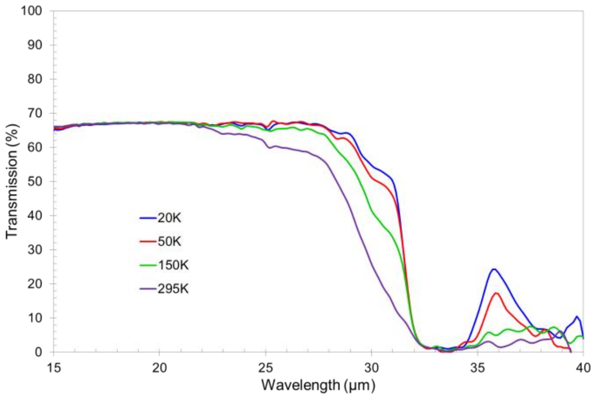

Fig 1. Uncoated CdTe substrate 3.7 mm thick
(295K – 20K)

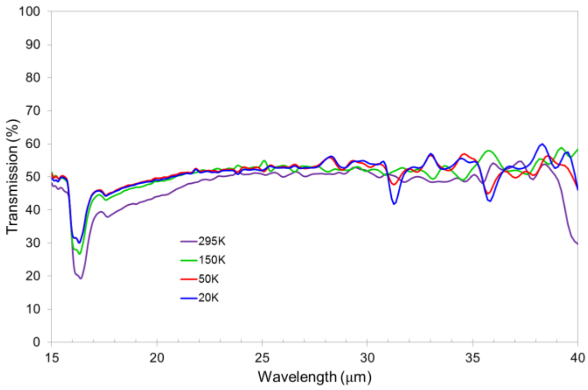

Fig 2. Uncoated Si substrate measurement
1.0 mm thick (295K - 20K)

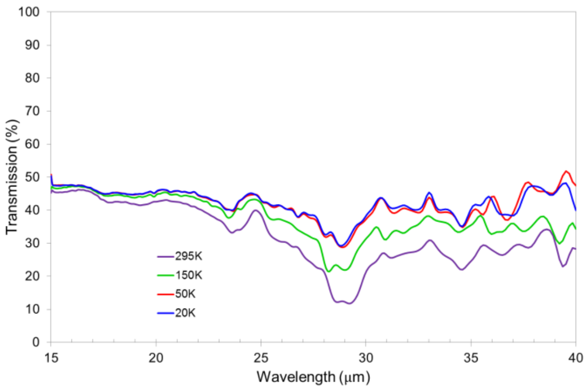

Fig 3. Uncoated Ge substrate measurement
0.4 mm thick (295K - 20K)

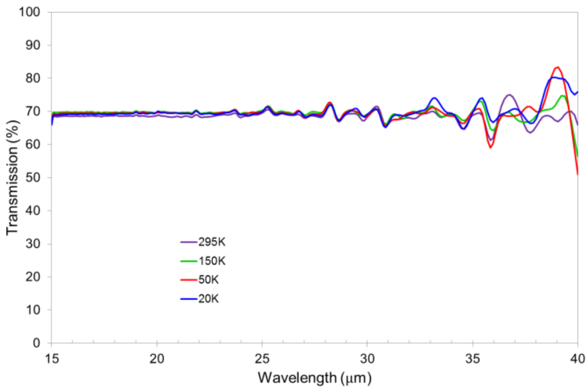

Fig 4. Uncoated Diamond substrate measurement
0.7 mm thick (295K - 20K)

3. MULTILAYER MATERIAL PROPERTIES

The availability of thin-film deposition layer materials with low stress and transparent optical properties in the *Q*-band region is limited, particularly where achieving highest antireflective transmission at the longest wavelength is paramount. The deposition of IV-VI lead telluride (PbTe) condenses in a polycrystalline face-centered cubic NaCl-type structure with an exceptionally high refractive index, which has been reported by us on former occasions [21] and provides many useful features. The unusual characteristics of the lead chalcogenides, such as a narrow bandgap with a positive temperature coefficient, high dielectric constant and large carrier mobility make it unique amongst polar semiconductors, and also valued as a thermoelectric material. Its high refractive index (n≈5.85 at 7K) in combination with various complementary II-VI low index dielectric materials provides one of the highest known refractive index contrasts and effective index (n*) to achieve spectral filtering with a minimum number of layers. It also possesses one of the longest wavelength semiconductor absorption edges at ~3.2 µm at 300K, shifting long-wave to ~5 µm at 7K, resulting from the anomalous narrowing of direct bandgap on cooling (≈ 0.4eV to ≈ 0.25eV). The advantage of this edge shift and spectral position provides blocking, removing the need for rejection by multilayer interference throughout the NIR and visible wavelength regions.

The selection of PbTe starting material and quality of high vacuum leads to the production of films with excellent and increasing transparent properties upon cooling to liquid nitrogen (77K) temperatures. However at lower temperatures (50-20K) there is a notable attenuation in transmission, where absorption starts to rise again. This increased absorption is considered to originate from the solid-state stoichiometric properties of the condensed PbTe films. Energy band calculations [22] indicate that PbTe possesses two valence bands, a light-hole band and heavy hole-hole band. The light-hole band varies dramatically with temperature, so at 300K the bandgap (~0.4 eV) exists between the heavy-hole band and conduction band, while at zero Kelvin the bandgap (~0.2 eV) is reduced between the light-hole band and conduction band. This prediction is coincident with the absorption edge moving to lower energy states (longer wavelengths) and with increasing refractive index at lower temperatures. However, in the absence of pure stoichiometry, the combination of Pb or Te atomic vacancies and interstitials are all present, with spectral effects that result from their defect state. There is currently no prescribed method to address how the effects of these defects interact with the energy band structure on cooling, and hence currently remains an anomaly in this area of thin-film fabrication and materials science. The consequence of maintaining stoichiometry under high vacuum therefore particularly requires the use of PbTe layers to be deposited with either non-stoichiometric source material containing Tellurium enrichment [23] or stoichiometric source material deposited within a partial pressure of oxygen [24], both of which exhibit similar spectral properties on cooling.

Together with PbTe, the selection of complementary low index materials with high durability and transparency across the *Q*-band requires high molecular weight dielectric compounds, of which CdSe is a preferred candidate. CdSe is a group II-VI dielectric with bandgap energy of 1.74 eV. It has long been found a useful material for optoelectronic devices such as solar cells, thin-film transistors, LED and electroluminescent devices. Deposition of CdSe possesses a high packing density, homogeneity, excellent adhesion, hardness and low stress. Two forms of CdSe are often used as evaporation material; low resistivity vacuum deposition grade sintered material, and single crystals prepared by high-pressure vertical zone melting, both of which are available commercially with 5N purity. An important consideration particular to the deposition of durable and transparent CdSe/PbTe based multilayers with high layer thicknesses are to ensure a high chamber vacuum ($<5\times10^{-5}$ Torr) is maintained throughout the deposition, together with the application of post-deposition annealing procedures.

4. FILTER PERFORMANCE

The design and fabrication of interference multilayers to isolate the *Q*-band region becomes increasingly complex with longer wavelengths. The multilayer thickness scales needed to define the spectral location are inevitably much thicker. This requires high evaporation rates and protracted deposition times with the consequence of cumulative film stress and material absorption. The optical and mechanical properties of the deposited thin-films differ from bulk material, being strongly dependant on the deposition method and conditions during film growth. The materials must fulfil criteria of high transparency, homogeneity, high packing density, low stress, hardness, adhesion and the ability to survive an extensive range of environmental and optical conditions. Particular importance is the specific refractive index to provide high contrast between H and L layers to reduce the number of layers, maintain low physical thickness and minimise wavelength shifts caused by tilted and nonparallel illumination.

A number of wide bandpass filters have been fabricated and characterised using PbTe/CdSe based multilayers. The shift in spectral positioning on cooling is a consequence of the thermal expansion coefficient (α_L) and temperature coefficient of index of refraction (dn/dT) of the multilayer, from which large long-wave shifts are exhibited across the passband as the temperature cools. As dn/dT is considerably greater than α_L, the net wavelength shift is dominated by the increasing refractive index of PbTe on cooling. This increases the rejection bandwidth of the multilayer stop-band, displacing the cut-on edge position to longer wavelengths. Prototype calibration of the multilayer designs and material properties are used to tune the filter to the desired bandwidth and centre wavelength. Figures 5-8 show the transmittance of a range of CdTe filters developed for an uncooled airborne far infrared radiometer [25] across a range of *Q*-band wavelengths at temperatures between 295K and 20K. Cooling of these filters has demonstrated robust durability and maintaining high transparency at low temperatures. The multilayer designs comprise overlapping combinations of refined Tschebysheff [26] polynomial designs, quarter-wave stacks, index-matching layers and broadband antireflection.

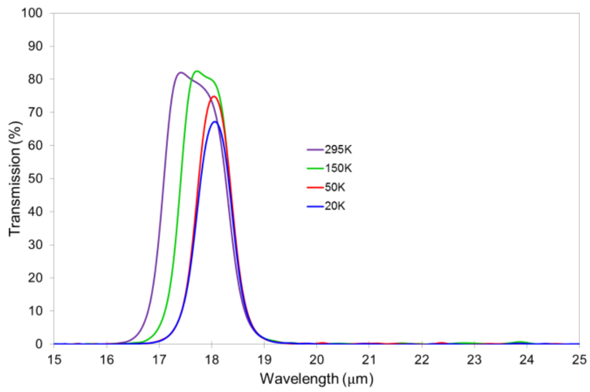

Fig 5. Cooled 18 μm 7.2% FWHM wide-bandpass filter at 295K, narrowing to 4.2% at 20K on CdTe

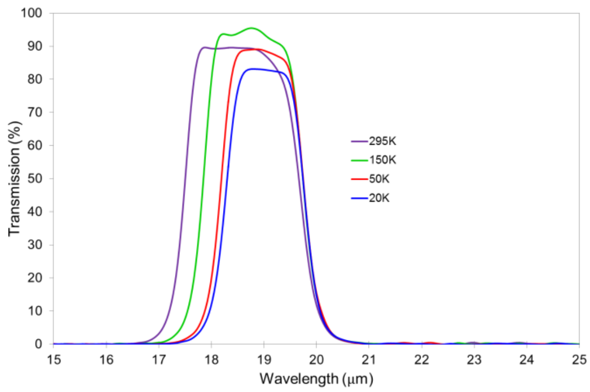

Fig 6. Cooled 19 μm 12.0% FWHM wide-bandpass filter at 295K, narrowing to 8.1% at 20K on CdTe

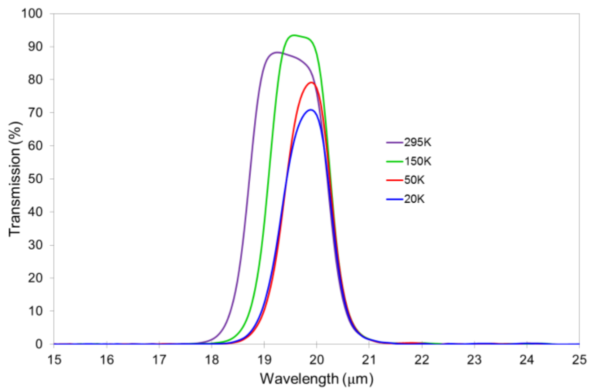

Fig 7. Cooled 20 μm 8.0% FWHM wide-bandpass filter at 295K, narrowing to 5.2% at 20K on CdTe

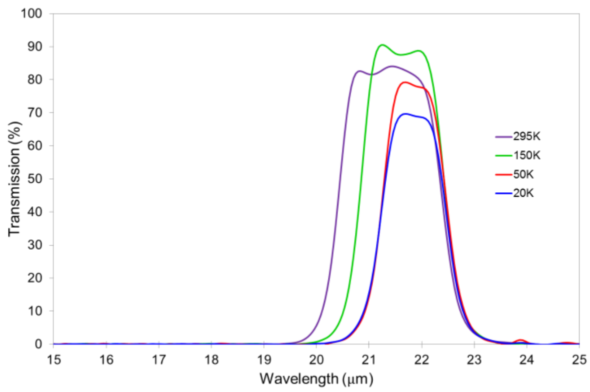

Fig 8. Cooled 22 μm 9.4% FWHM wide-bandpass filter at 295K, narrowing to 6.0% at 20K on CdTe

Figures 9-11 show the CdTe *Q*-band interference filters developed for the thermal–infrared wide-field imaging camera sub-system on the James Webb Space Telescope (JWST) Mid-Infrared Instrument (MIRI) [19]. These filters were designed and tested for operation at 7 K, and were required to survive repetitive cryogenic cooling with no evidence of stress fracture or deteoriation. The filters comprised combinations of long-wave and short-wave pass edge filters with overlapping rejection stop-bands to provide continuous wavelength blocking. Transmitted rejection levels of $<3x10^{-4}$ were designed to coincide with the semiconductor photo-absorption edge of PbTe, and multiphonon substrate absorption of CdTe substrate at 32.5 μm.

The 20-25 μm 20% FWHM wide bandpass filter shown in Fig 12 was designed and fabricated on thin germanium for an uncooled thermopile focal plane detector array on the Mars Climate Sounder [11] which is currently in operation to measure low altitude (0-20 km) temperature emission from the Martian surface. The compact mechanical design of the focal plane detector array meant that the germanium absorption band across the 20 μm region was not of major concern because the substrates were very thin (0.4 mm). Cooling of the filter to 20K has shown good spectral and mechanical performance of the coating across this waveband.

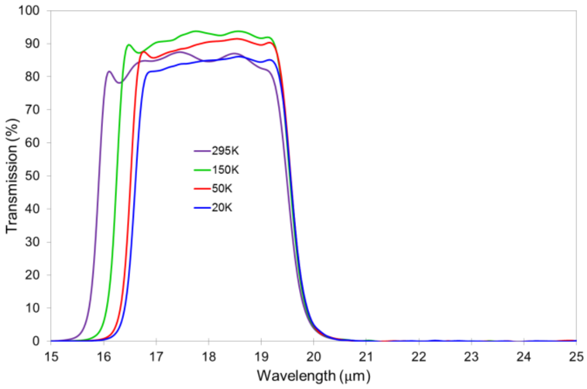

Fig 9. Cooled 18 µm 21% FWHM wide-bandpass filter at 295K, narrowing to 16.2% at 20K on CdTe

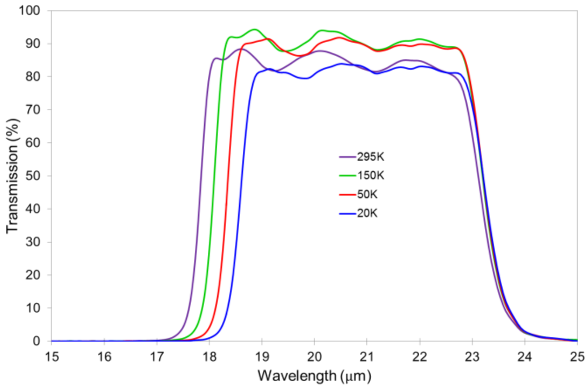

Fig 10. Cooled 21 µm 27% FWHM wide-bandpass filter at 295K, narrowing to 23% at 20K on CdTe

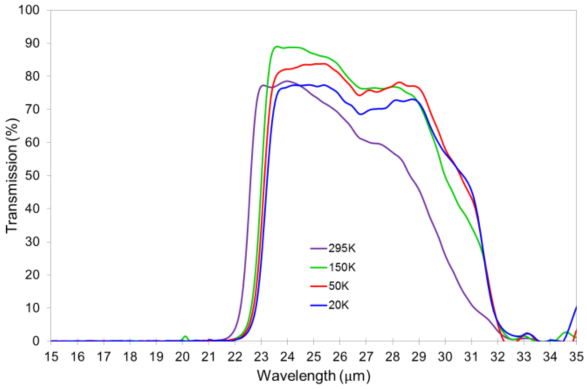

Fig 11. Cooled 23-30 µm long-wave pass edge on CdTe

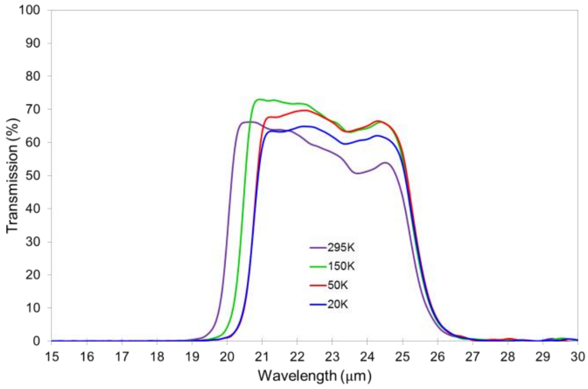

Fig 12. Cooled 23 µm 23% FWHM wide-bandpass filter at 295K, narrowing to 20% at 20K on Ge

5. TEMPERATURE-INVARIANT NARROW BANDPASS FILTERS

All of the lead (Pb) based chalcogenide semiconductor materials (PbTe, PbSe, PbS) exhibit unique thermo-optical properties. Their unusual negative temperature expansion coefficient ($dn/dT<0$) combined with the positive temperature coefficients ($dn/dT>0$) of II-VI dielectric materials enable narrow bandpass filters to be designed and fabricated with total immunity to wavelength displacement with temperature. The inherent temperature shift in centre wavelength of narrow bandpass filters is determined by the temperature interdependency of optical properties between the paired multilayer materials, involving refractive index contrast and physical layer thicknesses. For most materials, the temperature coefficients of these paired materials are positive, which leads to an optically thinner multilayer on cooling and subsequent short-wave displacement of centre wavelength. The bandpass immunity is a special case of thin-film design and construction which generates opposing temperature changes in refractive indices and thickness. These changes affect the crucial bandpass multilayer which comprises reflective quarter-wave (λ/4) thick layers surrounding multiple half-wave (λ/2, λ, 3λ/2 etc.) thick resonant cavities. These designs are especially constructed to generate alternate layer expansion coefficients that add up to zero. We have also performed research for the development of temperature-invariant behaviour in uncooled and high-temperature (20-200 °C) applications [27, 28].

The 25 µm temperature-invariant narrow bandpass filter illustrated in Figures 13 & 14 was designed with this invariant design principle using three low-index cavity layers of CdSe in combination with PbTe/CdSe paired reflectors. This design includes antireflection matching periods between the equivalent bandpass-core index [29] and surrounding media. The principle of temperature-invariance was first reported by Seeley *et al* [30] for a single cavity, from which the following principles were observed, i) the cavity layer in a Fabry-Perot bandpass filter is significantly more sensitive to thickness changes than the surrounding layers, ii) a double half-wave cavity thickness (λ) is twice as sensitive to thickness changes as a single half-wave cavity (λ/2), and iii) the reflector layers adjacent to the cavity are three times more sensitive than the successive inter-cavity layers. By extending and applying the design principles to a 3-cavity 25 µm narrow bandpass design, we have fabricated a 7% FWHM bandwidth filter with a centre wavelength temperature stability $d\lambda_0/dT < 0.1$ nm/K between 295 K and 20K, and out-of-band blocking intensity < 0.1%.

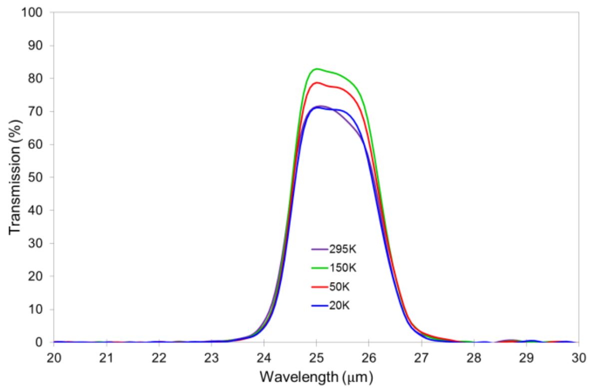

Fig 13. Temperature-invariant 25.3 µm narrow-bandpass filter (7% FWHM) cooling 295K-20K on CdTe.

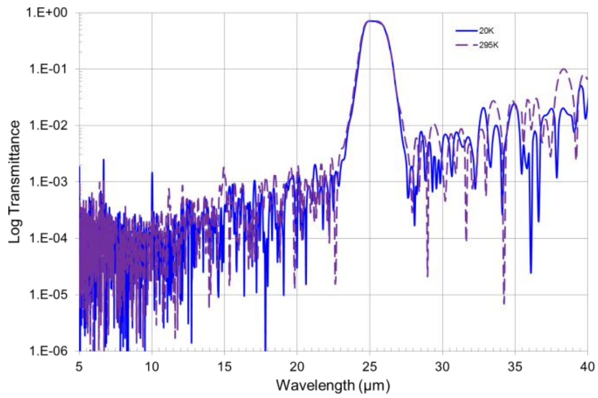

Fig 14. Blocking intensity of temperature-invariant narrow-bandpass filter on CdTe (295 & 20 K).

6. OTHER FIR EXPERIMENTAL INVESTIGATIONS

In order to determine the long-wavelength transparency performance and usefulness of thin-film materials in the 20 µm region, other experimental investigations of PbTe, CdSe, ZnSe and Ge multilayers were deposited on CVD diamond and silicon substrates [31]. As these materials possess a near absence of multiphonon absorption, the transmitted properties of the deposited films are distinct. To aid adhesion, diamond substrates were pre-coated with amorphous hydrogenated diamond-like carbon (DLC) precursor films as an adhesion-promoting layer. Attempts to further promote adhesion also used thin amorphous silicon monoxide and germanium pre-cursor films. These materials have been successfully deposited as multilayers to enhance coating adhesion on hard crystalline materials such as sapphire and silicon, which if deposited as a single thin layer retains transparency in the 20 µm region. Long-wave pass edge filters were fabricated at wavelengths of 20 µm and 23 µm using ZnSe/PbTe and CdSe/PbTe multilayers respectively (Fig. 15, 16). These filters were mechanically stable at temperatures down to 150K, below which the coatings fractured with compressive stress at the DLC interface. Spectral results show full transparency as thin-films for ZnSe/PbTe multilayers to wavelengths in the 29 µm region, and CdSe/PbTe to 40 µm. By using conventional thermal deposition techniques, the manufacture of robust cooled filters on diamond substrates at temperatures below 150K remains problematic, which although successful at room temperature, maybe of limited spectral advantage compared with other materials.

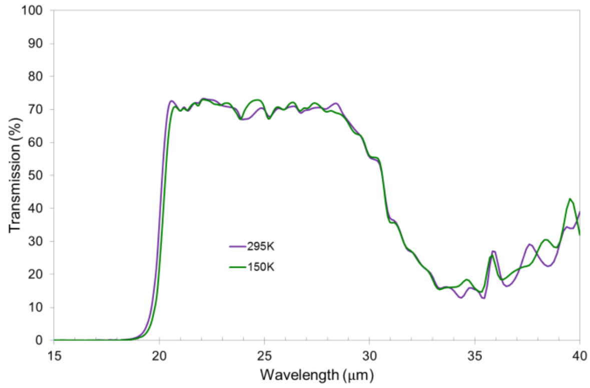

Fig 15. Cooling of PbTe/ZnSe/Ge/DLC 20-30 μm long-wave pass edge filter on diamond at 295K and 150K

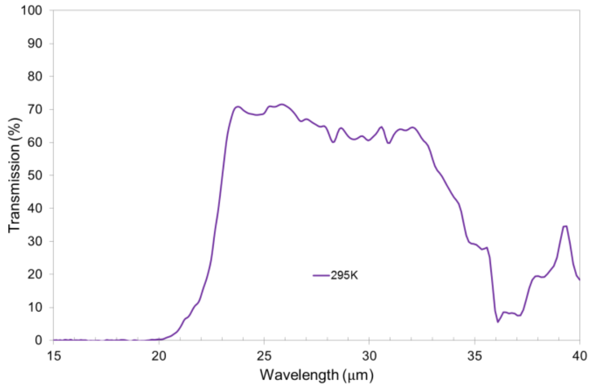

Fig 16. PbTe/CdSe/Ge/DLC 23-33 μm long-wave pass edge filter on diamond at 295K

To further assess the adhesion and cooling properties of thick CdSe/PbTe multilayers, investigations of transparency for long-wave pass edge filters were performed on silicon substrates across the 30-40 μm range (Figs. 17, 18). This has successfully resulted in a robust coating at room temperature and successfully passing adhesion tape tests. However, the effects of cooling increases the thermal expansion disparity between substrate and coating, resulting in compressive fracture at temperatures below 150K, and during thermal cycling. Other experimental investigations have also included; depositions to fabricate a narrow bandpass filter for molecular hydrogen [H_2 0-0 S(0)] transition in the 28.2 μm region, which although mechanically stable, resulted in unacceptably high absorption loss. Depositions of multilayers comprising CsI material (n=1.734 at 26 μm, 80K) to provide long-wave transparency also exhibited high absorption in combination with PbTe multilayers.

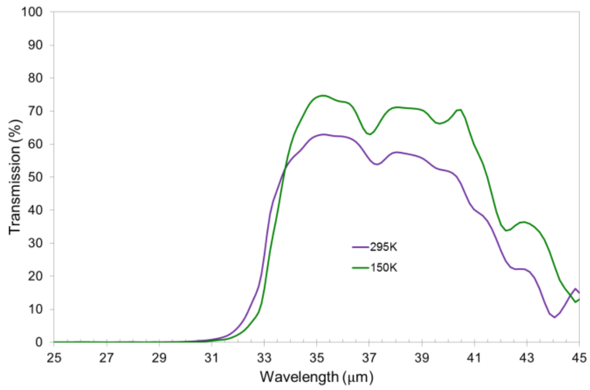

Fig 17. Cooling of 33-40 μm long-wave pass edge on Si at temperatures of 295K and 150K

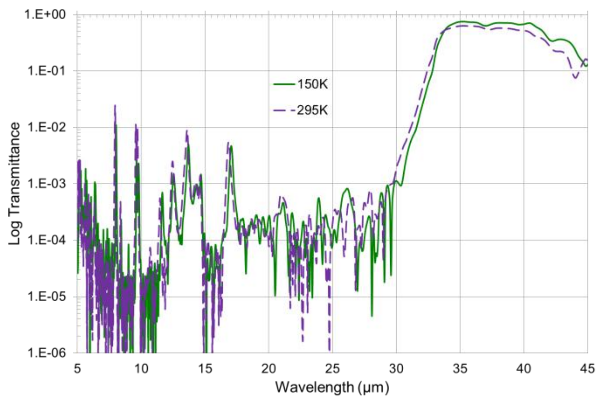

Fig 18. Cooling of 33-40 μm short-wave blocking intensity on Si at temperatures of 295K and 150 K

7. SPECTRAL MEASUREMENTS AND TESTING

Cooled transmission measurements over the Q-band region were performed at temperatures between 295K and 20K using a PerkinElmer Spectrum 2000 *Optica* Fourier transform spectrophotometer and auxiliary helium cryostat. The PE *Optica* instrument is the originating model of the PE-GX range. This instrument differs from conventional FTIR as it has been especially adapted to ensure high photometric accuracy [32] by supressing double-modulation inter-reflection aliasing that originates from stray light created by the highly reflective optical thin-film surfaces. This suppression is performed by half-apertures and masks strategically positioned along the optical train. The spectrometer has a high mid-IR energy grasp between 1.5–40 μm using a DTGS detector and Caesium Iodide (CsI) beamsplitter. Cooled measurements at the low temperatures were performed with single beam through a Sumitomo Displex DE202 cryostat cooled by a water-cooled helium compressor. The cryostat is positioned in the sample compartment with an *f*/8 beam focus and angled KRS-5 cryostat windows are used to compensate for beam displacement.

Environmental testing of all the cadmium based multilayers was shown to conform to military specification MIL-F-48616 and ISO specification 9211-3 for durability. These tests have included abrasion resistance, adhesion and humidity testing (50 °C at >95% relative humidity for 24 hours). In addition to this, witness samples were exposed to a 50-cycle thermal shock test involving unprotected direct immersions in liquid nitrogen at 77K followed by rapid transition to room temperature, all of which survived with no evidence of spectral or physical performance loss.

8. CONCLUSIONS

We have investigated and developed a range of durable cooled interference filters with PbTe and II-VI cadmium based materials capable of discriminating wavebands across the 15-30 μm *Q*-band region. Temperature-invariant narrow bandpass filters have also been developed for the 25 μm region and proven to show improvements on cooling with minimal shift of centre wavelength. Attempts to extend this region to longer wavelengths, beyond 30 μm using alternative substrate materials to fabricate cooled interference filters for operation below 150 K still remains an area of ongoing experimental research.

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