Large-area MEMS-based distributed Bragg reflectors for short-wave and mid-wave infrared hyperspectral imaging applications

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Abstract—We present the design, fabrication, and optical characterization, of silicon-air-silicon based distributed Bragg reflectors or quarter wavelength mirrors, in sizes ranging from $200\ \mu\text{m} \times 200\ \mu\text{m}$ to $5\ \text{mm} \times 5\ \text{mm}$. Such mirrors can be used in conjunction with either single-element photodetectors or large-area focal plane arrays to realise tunable multispectral sensors or adaptive focal plane arrays from the short-wave infrared wavelength ranges (1500-3000 nm) to mid-wave infrared wavelength (3000-6000 nm) ranges. Surface optical profile measurements indicate a flatness of the order of 20-30 nm in the fabricated structures across several millimetres. Single point spectral measurements on devices show excellent agreement with simulated optical models. The fabricated distributed Bragg reflectors show around 94% reflectivity, which is in close agreement with theoretical reflectivity. The demonstrated high reflectivity across a wide wavelength range, renders them suitable as broadband reflectors. Finally we present optical transmittance modelling results for Fabry-Pérot filters based on these distributed Bragg reflectors.

Keywords—Focal plane array, distributed Bragg reflector, Fabry-Pérot filter, short-wave infrared, mid-wave infrared.

I. INTRODUCTION

The short-wave infrared (SWIR) wavelength region and mid-wave infrared (MWIR) wavelength region are used extensively in image recognition, detection of trace chemical compounds, security and defense surveillance, and hyperspectral imaging [1]–[6]. MEMS based optical filters and distributed Bragg reflectors (DBRs) have penetrated many applications such as optical spectrometers, digital image projectors and imaging devices [7]–[9]. In this paper we present a silicon-air-silicon (3-layer) DBR or quarter-wave mirror (QWM) for use in MEMS based SWIR and MWIR wavelength range optical devices. We have fabricated DBRs varying in size from $200\ \mu\text{m} \times 200\ \mu\text{m}$ to $5000\ \mu\text{m} \times 5000\ \mu\text{m}$. The small size DBRs can be used in applications such as single-pixel MEMS field-portable spectrometers for stand-off detection [10] and the large DBRs can be used in hyperspectral imaging devices to realize large area adaptive focal plane arrays [11]. Fabricating the DBRs ranging in size from $200\ \mu\text{m} \times 200\ \mu\text{m}$ to several mm^2 raises challenges to control the properties of deposited silicon films. Important characteristics of these films include low surface roughness, low tensile stress and good optical

quality. A 3-layer DBR consists of two quarter-wave thick high refractive index dielectric layers separated by a quarter wave thick low refractive index material layer. The higher the contrast between the high and low refractive index, the higher the reflectivity of the DBR.

Taking advantage of mature silicon based technologies, many research groups have used bulk-micromachining of silicon to fabricate high quality in-plane silicon-air-silicon based DBRs in the SWIR wavelength band [12], [13]. These DBRs were small in size and designed for optical communication applications. A comprehensive overview of advances in in-plane silicon-air-silicon based DBRs can be found in Ref. [14]. Tuohiniemi *et al.* [15] fabricated Si-air-Si based DBRs for the long wave infrared (LWIR) wavelength range. In order to avoid stiction associated with wet release of the membranes, they used anti-stiction bumps at the expense of reduced effective optical area. Ebermann *et al.* [16] used multilayer silicon and silicon oxide structures to fabricate a highly reflecting DBR in the MWIR wavelength range. It was highlighted that use of such multi-materials in a DBR causes stress mismatch in the layers, which must be compensated for in order to achieve a flat surface profile for the DBRs. The same research group also fabricated a dual-band tunable Fabry-Pérot filter for MWIR and LWIR wavelength operation [17]. However, the aperture of the filters and DBRs was limited to 1.9 mm diameter. Kozak *et al.* [18] proposed integration of a DBR with a HgCdTe detector to create a Fabry-Perot interferometer centered in the MWIR spectrum. In order to avoid the tendency of warping due to imperfect optical surfaces, they used a SOI-MUMPS process to create the DBRs. With monolithically integrated approaches, one is limited by the choice of materials compatible with both the FPA and the MEMS-based tunable filter fabrication. Furthermore, monolithic integration cannot take full advantage of the myriad of available processes to optimize the stress and optical properties that are available exclusively to MEMS technologies, and the many optimization technologies available exclusively for detector fabrication. In this work we present the fabrication process of large-area silicon-air-silicon DBRs based on thin-film surface micromachining technologies. This is followed by a presentation of the optical measurements and modelling results.

II. OPTICAL MODELING OF DBRS

The optical transfer matrix modelling of a multilayer stack of thin films relates the electric and magnetic field at all

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the interfaces of optical thin films via a characteristic matrix. Details of the optical transfer matrix modelling can be found in standard references [19]. The optical transfer matrix model has been developed for normal and angled incidence on transparent and weakly absorbing substrates, by assuming that light enters from free space in a thin film with thickness d_1 and refractive index n_1 at θ_1 angle of incidence. If δ is the path difference created by the propagation through the thin film, then

$$\delta = \frac{2\pi}{\lambda} n_1 d_1 \cos \theta_1. \quad (1)$$

The characteristic matrix for the film can be given as

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos \delta_1 & (i/\eta_1) \sin \delta_1 \\ i\eta_1 \sin \delta_1 & \cos \delta_1 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_0 \end{bmatrix} \quad (2)$$

where η_0 is the optical admittance of free space. This result can be extended for a stack of m thin films, by simply multiplying the characteristic matrix of each film in the order of their appearance.

$$\begin{bmatrix} B \\ C \end{bmatrix} = \prod_{r=1}^m \left(\begin{bmatrix} \cos \delta_r & (i/\eta_r) \sin \delta_r \\ i\eta_r \sin \delta_r & \cos \delta_r \end{bmatrix} \right) \begin{bmatrix} 1 \\ \eta_{out} \end{bmatrix} \quad (3)$$

where

$$\delta_r = \frac{2\pi}{\lambda} n_r d_r \cos \theta_r \quad (4)$$

The optical admittance can be given as

$$\eta_r = n_r \cos \theta_r, \text{ for } s - \text{polarization (TE)} \quad (5)$$

$$\eta_r = n_r / \cos \theta_r, \text{ for } p - \text{polarization (TM)} \quad (6)$$

where η_{out} is the optical admittance of the output medium. The reflection and transmission coefficients for the dielectric stack are then given by

$$\rho = \frac{B\eta_0 - C}{B\eta_0 + C} \quad (7)$$

$$t = \frac{2\eta_0}{\eta_0 B + C}. \quad (8)$$

The reflectance of the dielectric stack can be expressed as

$$R = \left(\frac{B\eta_0 - C}{B\eta_0 + C} \right) \left(\frac{B\eta_0 - C}{B\eta_0 + C} \right)^* \quad (9)$$

Garmire [20] calculated that the highest reflectivity for a N order DBR can be achieved by having the high refractive index layer as the first layer receiving the incident signal from free space. For normal incidence at the central design wavelength λ_0 the reflectivity of a lossless N -period DBR deposited on a substrate with refractive index n_S having a high-index first layer is given by

$$R(N) = \left(\frac{1 - n_S(n_H/n_L)^{2N}}{1 + n_S(n_H/n_L)^{2N}} \right)^2 \quad (10)$$

and for a $N+1/2$ period DBR, by

$$R(N + 1/2) = \left(\frac{n_S - n_H^2(n_H/n_L)^{2N}}{n_S + n_H^2(n_H/n_L)^{2N}} \right)^2 \quad (11)$$

Equations 10 and 11 indicate that the reflectivity of a DBR is also dependent on the refractive index of the substrate. This refractive index determines the reflectivity of the interface between the last layer of the mirror and the substrate. The top mirror of a typical MEMS-based Fabry-Pérot filter is usually suspended in air so that $n_S = 1$, in which case the highest reflectivity is achieved with an $N+1/2$ period mirror, compared to either an $N+1$ period mirror or an $N-1$ period mirror. The reflectance finesse of the Fabry-Pérot filter F_R , is given by

$$F_R = \frac{\pi\sqrt{R}}{1-R}. \quad (12)$$

The full width at half maximum (FWHM) of a Fabry-Pérot filter $\delta\lambda$, is given by

$$\delta\lambda = \frac{\lambda}{F_R \left(m + \frac{1}{n_H - n_L} \right)} \quad (13)$$

where m is the operating order of the Fabry-Pérot filter. The free spectral range (FSR) can be expressed as

$$\Delta\lambda = \frac{\lambda}{\left(m + 1 + \frac{1}{n_H - n_L} \right)}. \quad (14)$$

Assuming that T_1 and T_2 are the transmittance through the top and bottom DBR of a Fabry-Pérot filter, the transmittance for the Fabry-Pérot filter can be expressed as [21]

$$T_F(\Psi) = \frac{\frac{T^2}{(1-R)^2}}{1 + \frac{4F_R^2}{\pi^2} \sin^2 \left(\frac{\Psi}{2} \right)} \quad (15)$$

$$T_F(\Psi) = \frac{T_{max}}{1 + \frac{4F_R^2}{\pi^2} \sin^2 \left(\frac{\Psi}{2} \right)} \quad (16)$$

where T_{max} is the peak transmittance, $T = \sqrt{T_1 T_2}$, and Ψ represents the round trip phase change. This mathematical model has been used in simulating theoretical models of DBRs and Fabry-Pérot filters.

III. STRUCTURAL DESIGN OF DBRS

An essential consideration for fabricating large area DBRs is the robustness of the support structure under stress caused by the large area suspended membrane. The design used for fabricating large area DBRs is shown in Fig. 1. In this design the suspended membrane has conformal support around the entire periphery, which provides the most robust support structure for a suspended membrane. The fabrication and characterization of the DBRs with this design is presented in this paper. The sacrificial material can be removed through the 5 μm diameter etch holes perforated in the top suspended membrane. The adjacent etch holes are 50 μm apart, thus, the average porosity of the second suspended silicon layer was reduced by less than 1%. With such a low porosity there is no impact on the refractive index and stress of the suspended silicon layer. In order to block stray light entering through the etch holes, metal pads with 8 μm diameter were deposited directly under each etch hole. The presence of the metal pads

reduces the effective optical area of the DBR by less than 1.5%, which is very minor and has no observed impact on the optical performance of the DBRs.

Fig. 1. Structural design of DBRs with conformal support around the entire periphery.

IV. EXPERIMENTAL

In this work, silicon has been used as the high refractive index material and air has been used as the low refractive index material in the DBRs. The underlying Si and SiO_x thin film layers were deposited on 300 μm thick $\langle 100 \rangle$ oriented silicon substrates using a *Sentech SI500D* inductively coupled plasma chemical vapour deposition (ICPCVD) system. A *Zygo Newview* white light optical surface profiler was used to measure surface flatness of the suspended top silicon layers. Table I gives the deposition parameters for ICPCVD SiO_x films, while Table II gives the deposition parameters for the Si films. In order to measure stress in the Si films, the thin films were deposited on 70 μm thick $\langle 100 \rangle$ Si substrates. By measuring stress induced bowing in the thin Si substrate and applying Stoney's formula [22], [23], the residual stress in deposited Si thin films was calculated, which was found to be dependent on the thickness of the deposited film. This dependency is shown in Fig. 2. A 50 nm thick silicon film shows 135 MPa of residual compressive stress, which reduces with an increase in the deposited thickness. At 150 nm thickness the silicon film shows 40 MPa of residual compressive stress which turns into 26 MPa of residual tensile stress for films with 275 nm thickness. After reaching 90 MPa of residual tensile stress at 500 nm thickness, the films again show residual compressive stress of 100 MPa for 700 nm thick films, which reduces to 30 MPa of residual compressive stress at 1000 nm thickness. The published literature shows similar dependency of stress on the thickness for PECVD oxides [24], [25]. Since the discussion of physical causes of such dependency of stress on thickness is beyond the scope of this paper, we will simply use these values in the fabrication process for DBRs.

V. FABRICATION PROCESS OF SILICON-AIR-SILICON BASED LARGE AREA DISTRIBUTED BRAGG REFLECTORS

Fig. 3 shows the fabrication flow of the Si-air-Si DBRs. The fabrication steps are listed as given below:

Fig. 2. Stress in ICPCVD deposited silicon thin films as a function of film thickness.

TABLE I. ICPCVD SiO_x DEPOSITION PARAMETERS.

ICP power (W)	Pressure (Pa)	Temperature (°C)	Flow rate (sccm)			
			SiH ₄	He	N ₂ O	Ar
450	2	130	6.5	123	70	120

TABLE II. ICPCVD DEPOSITION PARAMETERS FOR Si THIN FILMS.

ICP power (W)	Pressure (Pa)	Temperature (°C)	Flow rate (sccm)	
			SiH ₄	He
26	4	300	5	95

TABLE III. ACTUAL THICKNESS OF DEPOSITED LAYERS FOR MWIR AND SWIR DBRs.

Layer	Thickness (MWIR DBR) (nm)	Thickness (SWIR DBR) (nm)
SiO _x	200	200
Si [1]	345	158
Prolift100-16	1230-1300	500-520
Si [2]	335	145

- 1) As shown in Fig. 3(a) we start with a silicon substrate and deposit a 200 nm silicon oxide layer. This thickness was chosen simply for convenience, and was the same for both MWIR and SWIR devices. For an optimized DBR this layer should be one quarter wavelength thick. On top of the oxide layer a quarter wavelength thick silicon layer is deposited, which is the first optical layer of the DBR. For the MWIR and SWIR DBRs the target quarter wavelength thickness of silicon thin films was 350 nm and 145 nm, respectively. The actual deposited thickness of the deposited films was different from these values, and Table III shows the actual thickness of the deposited layers.
- 2) On top of the first silicon layer a chromium (10 nm)/gold (100 nm) metal bottom optical shield is deposited which also deposits optical signal blocking metal pads underneath the etch holes (see Fig. 3 (b)).

Fig. 3. Fabrication process of DBRs. (a) Deposition of quarter wavelength thick Si thin film on silicon oxide deposited substrate; (b) deposition of metal optical shield; (c) spinning, hard-baking and patterning of PL100-16 polyimide; (d) deposition of the second quarter wavelength thick Si thin film on top of polyimide; (e) patterning of etch holes through the top Si membrane; (f) dry release of DBR in the O_2 plasma.

- 3) Brewer science Prolift 100-16 was chosen as the sacrificial layer. Apex-k1-100 adhesion promoter was spun at 4000 rpm and baked at 150 °C for 30 seconds. In order to achieve a quarter wavelength thick air cavity, the Prolift100-16 was spun at 1800 rpm for MWIR DBRs and, at 4000 rpm for SWIR DBRs. The sacrificial layer was soft-baked at 100 °C for 2 minutes and then ramped to 250 °C for a total of 15 minutes to fully cure it. The sacrificial layer was wet patterned in AZ326 developer with a resulting thickness as shown in Table III (Fig. 3(c)).
- 4) After the removal of the photoresist a short oxygen plasma exposure was performed for 15 seconds, which improves adhesion of the top silicon layer to the sacrificial layer. On top of the sacrificial layer a second silicon layer was deposited, which conformally covers the sacrificial layer (Fig. 3(d)).
- 5) The top silicon layer was perforated with 5 μ m diameter etch holes using CF_4 plasma as shown in Fig. 3 (e). As shown in Fig. 2, silicon thin films with thickness around 150 nm will be compressive in nature, hence for SWIR DBRs a pre-release annealing at 260 °C for 30 minutes was performed in a quartz tube furnace in nitrogen ambient. The silicon thin films with thickness around 350 nm were tensile in nature, hence MWIR DBRs were not annealed. The dependence of residual stress on thin film thickness has been extensively reported by several authors [26], [27]. It was observed that the stress in thin films was initially compressive in nature, and that with increasing in thickness enters into a tensile region. A further increase in film thickness eventually renders it increasingly compressively stressed. Furthermore, Leib *et al.* [28], [29] explored the possibility of a reversible change in stress in the compressive stress region. Our findings of dependence of stress of silicon thin films on deposited thickness of silicon thin films, shown in Fig. 2, are in agreement with these previous studies.
- 6) The sacrificial layer was etched in an O_2 plasma in

a barrel Asher with 160 W RF power and 133.3 Pa chamber pressure. The removal of the sacrificial layer leaves the top membrane suspended over the bottom layer, thus forming an air cavity as shown in Fig. 3 (f).

DBRs ranging in size from 200 μ m $\times$ 200 μ m to 5 mm $\times$ 5 mm were fabricated using the above fabrication process. A microscope image of a 2 mm $\times$ 2 mm fabricated DBR is shown in Fig. 4.

Fig. 4. Micrograph of a 2 mm $\times$ 2 mm fabricated DBR.

VI. OPTICAL CHARACTERISATION OF DBRS

The effectiveness of the DBR fabrication process was assessed through optical characterization. Optical surface profilometry and optical transmittance measurements were chosen to optically characterize the DBRs.

A. Optical surface profilometry

A line scan across a 2 mm $\times$ 2 mm DBR for SWIR wavelengths is shown in Fig. 5 (a), and its expanded scale plot is shown Fig. 5 (b). Note the variation of the flatness in the center 1.45 mm length across the 2 mm mirror was found to be in the range of 10–20 nm. In this DBR the edges shows a sharp bowing of 40–50 nm. An expanded scale plot of the surface profile indicates the available optical area for the SWIR DBR, indicating a very low flatness variation of the order of 10–20 nm.

All fabricated MWIR and SWIR wavelength range DBRs, of all sizes, show sharp bowing at the edges, and have 70–75% of the fabricated area being optically flat to within a 20–30 nm range. This flat area can be designated as the optically active area because the variation in flatness within a 20–30 nm range will cause a very insignificant change in the optical performance of the DBRs. The sharp bowing at the edges of each DBR is most likely due to the anchor effect resulting from tensile stress in the silicon thin films. This bowing can be reduced by reducing the tensile stress from the present value to further lower values. The variation in bowing at the edge of the DBRs with variation in the stress in amorphous silicon thin films will be the subject of future study.

Fig. 5. (a) A line scan across surface profile of $2\text{ mm} \times 2\text{ mm}$ DBR in the SWIR wavelength range avoiding etch holes; (b) an expanded scale surface profile of (a).

B. Single point transmittance and reflectance spectrum of the fabricated DBRs

The optical transmission of DBRs was investigated using a Spectrum One FTIR spectrometer by Perkin Elmer. This system enables measurement of spectral transmission and absorption in the spectral range from $1.3\text{ }\mu\text{m}$ to $28.5\text{ }\mu\text{m}$ with high accuracy. The beam spot size for optical measurement of DBRs was $\geq 2\text{ mm} \times 2\text{ mm}$ in size which is much larger than the periodicity and size of the etch holes and metal pad patterns in the fabricated DBRs. Due to the large beam spot size, and the low density and small size of etch holes and metal pad patterns, we expect scattering effects on the final optical measurements to be negligible. However, with our current instrument setup and accessories, a specular reflection measurement was not possible. Hence a transmission measurement was used to estimate the reflectance of the DBRs.

Figure 6 shows the measured single point transmission (optical beam diameter of 1 mm), and the simulated and estimated reflectance for a $2\text{ mm} \times 2\text{ mm}$ DBR was 1 mm in diameter. The simulated spectra was obtained by the optical transfer matrix method described in Section II. The simulated

models used actual measured thicknesses and optical constants of ICPCVD silicon and silicon oxide layers. However, at this point the simulated models do not include the effect of surface variations. The extracted extinction coefficient of amorphous silicon thin films was negligible (in the order of 10^{-6}) in the SWIR and MWIR wavelength range, which indicates that the DBRs have negligible absorption. Hence, the percentage reflectance can readily be calculated from the measured percentage transmittance by direct subtraction from 100%. The “Calculated Reflectance” shows the final calculated reflectivity of fabricated DBRs.

Figure 6 (a) and (b) shows the optical spectrum of MWIR and SWIR DBRs, respectively. As shown in Fig. 6 (a) the measured minimum transmission of 5% compares well with the 4.5% predicted from the simulation. In comparison to the theoretical 94.5% reflectivity, we attained 94% peak reflectivity. The DBRs show more than 85% reflectivity over the 3750 nm – 6000 nm wavelength range. The reflectivity is close to 93% in the wavelength range 4100 – 4910 nm . Figure 6 (b) shows that 5.7% is the minimum measured transmittance of SWIR DBRs, which compares well with the theoretical 5.2% predicted for the simulated model. The SWIR DBR shows 94.3% reflectivity as compared to 94.8% simulated reflectivity. The SWIR DBRs show more than 85% reflectivity over the 1950 nm – 2700 nm wavelength range. Thus, the very flat surface profile variation and high reflectivity over a wide wavelength range can be effectively utilized in a range of spectroscopic imaging systems. It is to be noted that the fabricated DBR can deliver the highest performance by choosing a quarter wavelength thick silicon oxide layer on the substrate. Figure 6 (a) and (b) show “Simulated Reflectance (QW SiO_x)”, which is the simulated reflectivity of DBRs with a quarter wavelength thick silicon oxide layer. For the MWIR wavelength range DBRs, the quarter wavelength thickness of silicon oxide layer is 868 nm . Figure 6 (a) shows that the peak reflectivity for the MWIR wavelength range DBRs increases to 97%, which gives an improvement of 3% for the peak reflectivity. The DBR shows more than 85% reflectivity over the 3540 nm – 7510 nm wavelength range, which is an increase of 1720 nm as compared to the fabricated MWIR wavelength range DBRs. In the same way, by choosing a 347 nm thick oxide layer for the SWIR DBR, the peak reflectivity can be increased to 97% and more than 85% reflectivity can be obtained over the 1920 nm – 3390 nm wavelength range. Hence, an optimized Si-air-Si based DBR should have a quarter wavelength thick underlying silicon oxide layer in order to achieve maximum reflectivity and widest bandwidth. Fabrication of such DBRs will be included as part of our future work of fabricating Fabry-Pérot filters based on Si-air-Si DBRs.

C. Fabry-Pérot filter based on Silicon-air-silicon DBRs

A schematic layout for the proposed Fabry-Pérot filter based on Si-air-Si DBRs is shown in Fig. 7(a), and a cross section is shown in Fig. 7(b). The filter layout is applicable to filters of size $200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$, to $1000\text{ }\mu\text{m} \times 1000\text{ }\mu\text{m}$. With some modification to the size of the electrodes and notches, this structure can be adapted for even larger filter sizes. The

Fig. 6. The transmittance and reflectance of the fabricated DBRs. Measured Transmittance—measured transmittance data; Calculated Reflectance—DBR reflectance based on fitted transmission. Simulated Reflectance—expected reflectance of DBR; Simulated Reflectance (QW SiOx)—expected reflectance of DBR by choosing quarter wavelength thick silicon oxide layer; (a) Transmittance and reflectance values for the MWIR DBRs (b) transmittance and reflectance of SWIR DBRs shown in Fig. 5.

top mirror and bottom mirror are made of Si-air-Si DBRs, with each silicon layer in this structure being quarter wavelength thick. An optical area $10\text{ }\mu\text{m}$ smaller than the mirror dimension is opened through the optical signal blocking metal shield deposited on the backside of the substrate. The four top electrodes and four bottom electrodes provide symmetric actuation movement to the top DBR. A specific feature of the top membrane are the notches at the four corners of the top DBR which allow the top membrane to actuate without causing stress induced distortion in the top DBR. The sacrificial layer is etched through the etch holes. Unwanted optical signal through the etch holes is blocked with the help of metallic optical blocking pads underneath each etch hole.

In order to confirm the suitability of the DBRs for tunable Fabry-Pérot filters for hyperspectral imaging applications, we modelled the optical transmission of the filter structure shown in Fig. 7 using the optical transfer matrix model discussed in

Fig. 7. Graphical layout for the proposed Fabry-Pérot filter. (a) Shows a top view; (b) shows cross section through filter.

Section II. A 310 μm thick silicon substrate was used as the substrate in the model. Next, a silicon oxide layer of optimum thickness is placed on top of the substrate. For the SWIR and MWIR wavelength range region the quarter wave thickness of silicon oxide layer was chosen as 470 nm and 1035 nm, respectively. Both the bottom and top DBRs consisted of silicon-air-silicon mirrors, separated by a tunable air cavity gap. For the SWIR and MWIR wavelength range DBRs, the quarter wave thickness of the silicon layers was chosen as 197 nm and 440 nm, respectively, and the quarter wavelength thick air gap within the DBRs was chosen as 675 nm and 1500 nm, respectively. The initial length of the tunable air cavity for the MWIR wavelength range and SWIR wavelength range operation was chosen as 3000 nm and 1350 nm, respectively, which allows the Fabry-Pérot filters to operate over the entire high reflectivity region of the DBRs. The cavity length of the filters was tuned to obtain the transmittance spectrum. Figure 8 (a) and (b) shows modelling results for the MWIR and SWIR filters, respectively. As shown in Fig. 8 (a) the modelling

predicts that a MWIR wavelength range filter based on Si-air-Si DBRs will have a peak transmission $> 80\%$, a minimum 30 nm FWHM, and a maximum 1850 nm FSR, thus resulting in a finesse of 61.7 and a quality factor of 200. Fig. 8 (b) shows that a SWIR filter is expected to have a peak transmission $> 60\%$, a minimum 15 nm FWHM, a maximum 850 nm FSR, a finesse of 70, and a quality factor of 180. It can be seen from Fig. 8 that as the filter is tuned to the shorter wavelength range of the DBRs, the FWHM widens and the out of band rejection ratio reduces significantly due to the lower mirror reflectivity at these shorter wavelengths. This modelling suggests that high finesse and broad FSR filters can be readily realized using Si-air-Si based DBRs. Table IV shows a summary of the optical results for the fabricated DBRs and modelled filters. In this table $\Delta\lambda$ indicates the maximum shift in the small-area spot scan peak transmittance across the active optical area of a filter due to the experimentally measured flatness variation across the fabricated DBRs.

VII. CONCLUSION

In this paper we have presented the design and fabrication process of silicon-air-silicon based distributed Bragg reflectors, operating in the SWIR and MWIR wavelength ranges, and ranging in sizes from $200\ \mu\text{m} \times 200\ \mu\text{m}$ to $5\ \text{mm} \times 5\ \text{mm}$. The variability of sizes allows them to be used in conjunction with either single-element photodetectors or large-area focal plane arrays. The fabricated DBRs demonstrate a 20-30 nm variation in flatness across several millimetres in dimension. Single point spectral measurements on devices show excellent agreement with simulated optical models. The fabricated distributed Bragg reflectors have around 94% reflectivity compared to the theoretical 95-96% reflectivity. Modelling of Fabry-Pérot filters based on these distributed Bragg reflectors indicated high finesse, narrow FWHM, and wide FSR for both the SWIR and MWIR wavelength ranges.

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REFERENCES

- [1] M. J. Cantelia, "Space surveillance with medium-wave infrared sensors," *The Lincoln Laboratory Journal*, vol. 1, no. 1, pp. 75–88, 1988.
- [2] E. Ochoa, T. Nelson, R. Bedford, J. Ehret, L. Starman, M. Harvey, T. Anderson, and F. Ren, "Demonstration of hybrid $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ -Polysilicon microelectromechanical tunable filter," *IEEE Photonics Technology Letters*, vol. 19, no. 6, pp. 381–383, 2007.
- [3] M. K. Griffin, Hsiao-Hua, K. Burke, and J. P. Kerekes, "Understanding radiative transfer in the midwave infrared, a precursor to full spectrum atmospheric compensation," in *Proceedings of SPIE*, vol. 5425, 2004, pp. 348 – 356.

Fig. 8. The modelled transmittance of Fabry-Pérot filters based on Si-air-Si DBRs. (a) Shows transmittance of MWIR filter; (b) shows transmittance of SWIR filter.

- [4] L. Rousset-Rouviere, C. Coudrain, S. Fabre, I. Baarstad, A. Fridman, T. Loke, S. Blaaberg, and T. Skauli, "Sysiphe, an airborne hyperspectral imaging system for the VNIR-SWIR-MWIR-LWIR region," in *Proceedings of 7th EARSel Workshop on Imaging Spectroscopy*, vol. 5, 2004, pp. 1 – 12.
- [5] F. Felder, M. Arnold, M. Rahim, C. Ebner, and H. Zogg, "Tunable lead-chalcogenide on Si resonant cavity enhanced midinfrared detector," *Applied Physics Letters*, vol. 91, no. 10, p. 101102, 2007.
- [6] N. Osia and T. Bourlai, "A spectral independent approach for physiological and geometric based face recognition in the visible, middle-wave and long-wave infrared bands," *Image and Vision Computing*, vol. 32, no. 11, pp. 847 – 859, 2014.
- [7] J. Dell, A. Keating, J. S. Milne, J. Antoszewski, C. Musca, L. Faraone, D. Murphy, and O. Samardzic, "Micro-electromechanical systems-based microspectrometers covering wavelengths from 1500 nm to 5000 nm," in *SPIE Defense and Security, Florida, USA*, 2007.

TABLE IV. SUMMARY OF OPTICAL RESULTS OF FABRICATED DBRS AND MODELLED FABRY-PÉROT FILTERS.

Wavelength Range	DBR or Quarter-wave mirror			Modelled Filter			
	Flatness variation of fabricated DBRs (nm)	Active optical area of (nm)	Wavelength range for 2 mm × 2 mm DBR	FWHM Reflectivity >85%	FSR (nm)	Peak Transmittance (nm)	$\Delta\lambda$ (%)
SWIR (1500 nm–3000 nm)	± 20	1.45 mm × 1.45 mm	1950 nm–2700 nm	15	850	>60%	± 30
MWIR (3000 nm–6000 nm)	± 30	1.55 mm × 1.55 mm	3750 nm–6000 nm	30	1850	>80%	± 15

- [8] R. A. Crocombe, “MEMS technology moves process spectroscopy into a new dimension,” *Spectroscopy Europe*, vol. 16, no. 3, pp. 16–19, 2000.
- [9] P. F. V. Kessel, L. J. Hornbeck, R. E. Meier, and M. R. Douglass, “A MEMS-based projection display,” in *Proceedings of the IEEE*, vol. 86, 1998, pp. 1686–1704.
- [10] J. S. Milne, J. M. Dell, A. J. Keating, and L. Faraone, “Widely tunable MEMS-based FabryPerot filter,” *Journal of Microelectromechanical Systems*, vol. 18, no. 4, pp. 905–913, 2009.
- [11] P. J. Treado, I. W. Levin, and E. N. Lewis, “Indium antimonide (InSb) focal plane array (FPA) detection for near-infrared imaging microscopy,” *Applied Spectroscopy*, vol. 18, pp. 607–615, 1994.
- [12] A. Lipson and E. M. Yeatman, “A 1-D photonic band gap tunable optical filter in <110> silicon,” *Journal of micromechanical systems*, vol. 16, no. 3, pp. 521–527, 2007.
- [13] B. Saadany, M. Malak, F. Marty, Y. Mita, D. Khalil, and T. Bourouina, “Electrostatically-tuned optical filter based on silicon bragg reflectors,” in *IEEE/LEOS international conference on optical MEMS and their applications*, 2006, pp. 86–87.
- [14] R. St-Gelais, A. Poulin, and Y. A. Peter, “Advances in modeling, design, and fabrication of deep-etched multilayer resonators,” *Journal of Lightwave Technology*, vol. 30, no. 12, pp. 1900–1908, 2012.
- [15] M. Tuohiniemi and M. Blomberg, “Surface-micromachined silicon air-gap bragg reflector for thermal infrared,” *Journal of Micromechanics and Microengineering*, vol. 21, no. 7, pp. 075 014[1–7], 2011.
- [16] M. Ebermann, K. Hiller, S. Kurth, and N. Neumann, “Design, operation and performance of a Fabry-Perot-Based MWIR microspectrometer,” in *Proceedings-OPTO 2009 and IRS² 2009*, 2009, pp. 233–238.
- [17] M. Meinig, M. Ebermann, N. Neumann, S. Kurth, K. Hiller, and T. Gessner, “Dual-band MEMS FABRY-PEROT filter with two movable reflectors for mid- and long-wave infrared microspectrometers,” in *16th International Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS)*, 2011, pp. 2538 – 2541.
- [18] D. A. Kozak, B. Fernandez, M. L. Morley, S. Velicu, and J. Kubby, “Fabrication and testing of a MEMS-based optical filter combined with a HgCdTe detector,” in *Proc. SPIE MOEMS and Miniaturized Systems X*, vol. 7930, 2010.
- [19] H. A. Macleod, *Thin-Film Optical Filters*. Institute of Physics, London, 2001.
- [20] E. Garmire, “Theory of quarter-wave-stack dielectric mirrors used in a thin Fabry-Perot filter,” *Appl. Opt.*, vol. 42, no. 27, pp. 5442–5449, Sep 2003.
- [21] J. M. Vaughan, *The Fabry-Perot Interferometer History, Theory, Practice and Applications*. Taylor and Francis, New York, 1989.
- [22] G. G. Stoney, “The tension of metallic films deposited by electrolysis,” *Proceedings of Royal Society*, vol. 82, pp. 172–175, 1909.
- [23] X. Feng, Y. Huang, and A. J. Rosakis, “On the Stoney’s formula for a thin film/substrate system with non-uniform substrate thickness,” *Journal of Applied Mechanics*, vol. 74, pp. 1276–81, 2007.
- [24] V. Au, C. Charles, D. A. P. Bulla, J. D. Love, and R. W. Boswell, “Thickness-dependent stress in plasma-deposited silicon dioxide films,” *Journal of Applied Physics*, vol. 97, no. 8, pp. 84 912[1–7], 2005.
- [25] R. Lathlaen and D. A. Diehl, “Stress in thin films of silane vapor-deposited silicon dioxide,” *Journal of Electrochemical society*, vol. 116, no. 5, pp. 620–622, 1969.
- [26] A. L. Shull and F. Spaepen, “Measurements of stress during vapor deposition of copper and silver thin films and multilayers,” *Journal of Applied Physics*, vol. 80, no. 11, pp. 6243–6256, 1996.
- [27] F. Spaepen, “Interfaces and stresses in thin films,” *Acta Materialia*, vol. 48, pp. 32–41, 2000.
- [28] J. Leib, R. Mönig, and C. V. Thompson, “Direct evidence for effects of grain structure on reversible compressive deposition stresses in polycrystalline gold films,” *Phys. Rev. Lett.*, vol. 102, p. 256101, Jun 2009.
- [29] J. Leib and C. V. Thompson, “Weak temperature dependence of stress relaxation in as-deposited polycrystalline gold films,” *Phys. Rev. B*, vol. 82, p. 121402, Sep 2010.

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