Thermal noise reduction and absorption optimization via multimaterial coatings

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Future gravitational wave detectors (GWDs) such as Advanced LIGO upgrades and the Einstein Telescope are planned to operate at cryogenic temperatures using crystalline silicon (cSi) test-mass mirrors at an operation wavelength of 1550 nm. The reduction in temperature in principle provides a direct reduction in coating thermal noise, but the presently used coating stacks which are composed of silica (SiO_2) and tantala (Ta_2O_5) show cryogenic loss peaks which results in less thermal noise improvement than might be expected. Due to low mechanical loss at low temperature amorphous silicon (aSi) is a very promising candidate material for dielectric mirror coatings and could replace Ta_2O_5. Unfortunately, such an aSi/SiO_2 coating is not suitable for use in GWDs due to high optical absorption in aSi coatings. We explore the use of a three material based coating stack. In this multimaterial design the low absorbing Ta_2O_5 in the outermost coating layers significantly reduces the incident light power, while aSi is used only in the lower bilayers to maintain low optical absorption. Such a coating design would enable a reduction of Brownian thermal noise by 25%. We show experimentally that an optical absorption of only (5.3 ± 0.4) ppm at 1550 nm should be achievable.

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I. INTRODUCTION

Future gravitational wave detectors (GWDs) such as Advanced LIGO upgrades and the low frequency (LF) detector within the Einstein Telescope (ET) [1,2] are planned to operate at cryogenic temperature to reduce thermal noise. Operation at low temperatures requires a replacement substrate material for the presently used fused silica test-mass mirrors. Showing low mechanical loss at low temperatures [3], crystalline silicon (cSi) is planned to be used at an operation wavelength of 1550 nm to keep optical absorption low [4]. 120 and 20 K are interesting operation temperatures for cSi with low thermoelastic noise due to zero crossings of the thermal expansion coefficient a_{th}. For ET an even lower operation temperature of 10 K is planned [1].

Coating thermal noise power spectral density is also proportional to the temperature of the coating, and so a reduction in temperature should in principle provide a direct reduction in thermal noise. However, the mechanical loss of many materials is temperature dependent, and cryogenic loss peaks have been identified in a doped Ta_2O_5/SiO_2 coating stack [5] and in single layers of SiO_2 [6] and Ta_2O_5 [7]. As a result of this increase in loss at low temperature, there is less thermal noise improvement than might be expected from operation at cryogenic temperature. Therefore, low mechanical loss at low temperature makes amorphous silicon (aSi) a very promising candidate material for dielectric mirror coatings and could replace Ta_2O_5 in the presently used coatings as a first step in improving the overall coating loss.

A standard highly reflective (HR) quarter-wavelength coating is composed of a stack of alternating materials of differing refractive indices, where each layer has an optical thickness $\delta = n \times t = \lambda/4$ (where t is the geometric thickness) for the wavelength of interest. The reflectivity depends on the number of bilayers in the coating, and on the difference in refractive index between the two materials. Thus, for a desired reflectivity, the total thickness of coating required depends on the difference in refractive index between the materials used.

Presently, stacks of alternating layers of SiO_2 and Ta_2O_5 are used as highly reflective coatings for GWD test-mass mirrors. aSi has a significantly higher refractive index than Ta_2O_5 ($n_{Si} = 3.5$ and $n_{Ta_2O_5} = 2.2$ at 1550 nm). Thus in comparison to a Ta_2O_5/SiO_2 coating, a coating formed from aSi/SiO_2 will have thinner high-index layers, and will achieve the same reflectivity with fewer bilayers. While a Ta_2O_5/SiO_2 coating stack requires 18 bilayers (plus a $\lambda/2SiO_2$ protection layer and a $\lambda/4Ta_2O_5$ transitional layer) to achieve a high reflectivity with a transmission of $T \approx 0.5$ ppm, a aSi/SiO_2 stack needs only 8 bilayers to achieve equivalent reflectivity.

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This significantly reduces the total thickness of the coating stack from 8.7 μm to 3.7 μm and provides a direct reduction in coating thermal noise. Furthermore, the cryogenic mechanical loss of aSi is at least a factor of 10 lower than that of Ta_2O_5, providing another direct reduction in coating thermal noise.

However preliminary studies of the optical absorption of a highly reflective Si/SiO_2 coating stack at 1550 nm have shown an absorption level of approximately 1000 ppm [8] which is substantially above the coating absorption requirement of future GWDs (which is in the order of 1 ppm). Thus optical absorption in aSi coatings would need to be significantly reduced for such a two-material arrangement containing aSi to be implemented.

In this paper we explore the use of multimaterial coatings and use measurements of aSi, Ta_2O_5 and SiO_2 to demonstrate the optical and thermal noise performance of a three material coating. A more general theory of multimaterial coatings, derived independently and in parallel to the work presented here, is given by Yam *et al.* [9]. Here we investigate a three material design in which low absorption Ta_2O_5 (combined with SiO_2) is used as the high-index material in the outermost 7 bilayers (plus a $\lambda/2SiO_2$ protection layer and a $\lambda/4Ta_2O_5$ transitional layer), which reflect more than 99.65% of the incident light power, while aSi is used as the high-index material in the 5 lower bilayers, which can tolerate the higher optical absorption due to the relatively low light power present. This design should in principle allow the higher refractive index and lower mechanical loss of aSi to be exploited, without significantly reducing the optical performance of the coating stack.

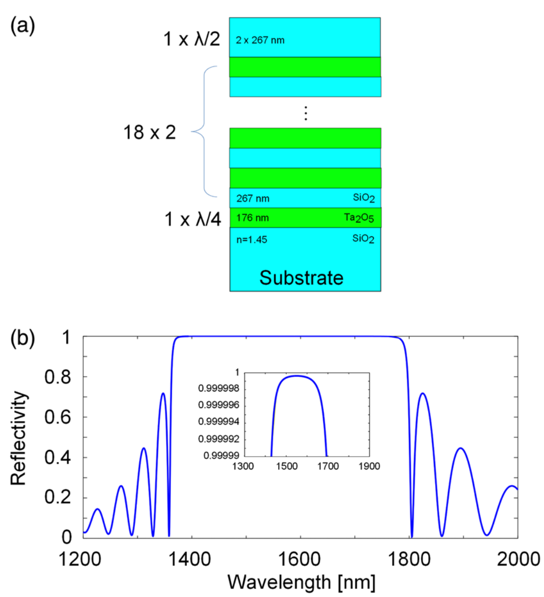

FIG. 1 (color online). (a) Schematic of a coating stack which consists of 18 $\lambda/4$ bilayers of alternating SiO_2 and Ta_2O_5 plus a $\lambda/2SiO_2$ protection layer on the surface and a $\lambda/4Ta_2O_5$ transition layer. The quarter layer thicknesses are $t_{SiO_2} =$ 267 nm and $t_{Ta_2O_5} = 176$ nm, resulting in a total thickness of 8.684 μm. (b) The transmission of this stack versus wavelength. At 1550 nm the transmission is $T \approx 0.5$ ppm.

II. MODEL OF THE MULTIMATERIAL COATING STACK

For the arm cavity end test mass (ETM) in cryogenic ET it is planned to use coating stacks of 18 $\lambda/4$ bilayers of alternating SiO_2 and Ta_2O_5 [1]. The refractive indices at 1550 nm are $n_{SiO_2} = 1.45$ and $n_{Ta_2O_5} = 2.2$. At each layer boundary the change of refractive index causes a reflection following Fresnel's equations [10]. Using ray-transfer matrix formalism for calculating a series of reflecting boundaries, the actual reflectivity within each bilayer of the coating stack was calculated (for details see [11]). Additionally to 18 $\lambda/4$ bilayers, our model stack has a $\lambda/2$ protection layer of SiO_2 on the outside surface and a $\lambda/4Ta_2O_5$ transitional layer between substrate and the first SiO_2/Ta_2O_5 bilayer starting with SiO_2. The total reflectivity of the stack is $R = 99.99995\%$ $(T = 1 - R \approx 0.5$ ppm). The total thickness of the stack is 8.684 μm of which 5.340 μm consist of SiO_2 and 3.344 μm of Ta_2O_5. A schematic of this model stack is shown in Fig. 1(a), while

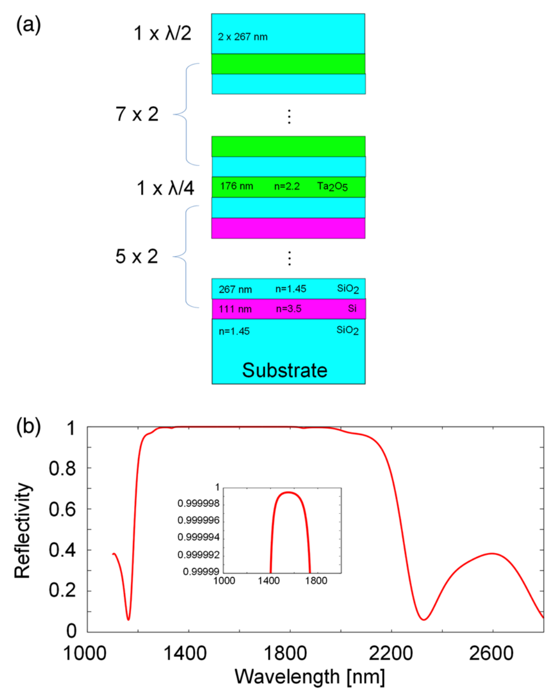

FIG. 2 (color online). (a) Schematic of the multimaterial coating stack. The stack consists of 7 $\lambda/4$ bilayers of alternating SiO_2 and Ta_2O_5 plus a $\lambda/2SiO_2$ protection layer on the surface and a $\lambda/4Ta_2O_5$ transition layer. Below this stack another 5 $\lambda/4$ bilayers of alternating aSi and SiO_2 follow. The quarter layer thicknesses are $t_{SiO_2} = 267$ nm, $t_{Ta_2O_5} = 176$ nm and $t_{Si} =$ 111 nm, resulting in a total thickness of 5.701 μm for the multimaterial coating stack. (b) The transmission of the multimaterial stack versus wavelength. Equivalent to the SiO_2/Ta_2O_5 stack the transmission at 1550 nm is $T \approx 0.5$ ppm.

TABLE I. Thickness t for the SiO_2/Ta_2O_5 coating stack, for the multimaterial stack ($SiO_2/Ta_2O_5/aSi$) and for the individual materials, and Young's modulus Y of the individual materials.

	SiO_2/Ta_2O_5		Multimat.		
t_{total} (μm)	8.684		5.701		
	SiO_2	Ta_2O_5	SiO_2	Ta_2O_5	aSi
t (μm)	5.34	3.344	3.738	1.408	0.555
Y (GPa)	72	147	140	98	96

Fig. 1(b), shows the reflectivity of the coating stack versus wavelength.

In a next step we explore a coating stack which starts with 7 bilayers of SiO_2/Ta_2O_5 (plus a $\lambda/2$ protection layer of SiO_2 and a Ta_2O_5 transitional layer) to reflect most of the laser light. Only 0.35% of laser light is transmitted by this stack. Additionally, 5 bilayers of aSi/SiO_2 are used to reduce the total transmission to $T \approx 0.5$ ppm; see Fig. 2. This reduces the number of single layers from 38 to 26 while the total thickness of the stack is reduced from 8.684 μm to 5.701 μm (by 34%). In Table I the total thicknesses of the coating stacks and of each material are listed.

III. THERMAL NOISE OF THE COATING STACK

The power spectral density of the coating thermal noise is proportional to both the mechanical loss and the total thickness of the coating stack as shown in Eq. (1) [12]:

$$S_x(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{1-\sigma^2}{w_0Y}\Big\{\phi_{\text{substrate}} + \frac{1}{\sqrt{\pi}}\frac{d}{w_0}\frac{1}{YY'(1-\sigma'2)(1-\sigma^2)} \times [Y'^2(1+\sigma)^2(1-2\sigma)^2\phi_\parallel + YY'\sigma'(1+\sigma)(1+\sigma')(1-2\sigma)(\phi_\parallel-\phi_\perp) + Y^2(1+\sigma')^2(1-2\sigma')^2\phi_\perp]\Big\}, \quad (1)$$

where f is the frequency in Hz, T is the temperature in Kelvin, Y and σ are the Young's modulus and Poisson's ratio of the substrate, Y' and σ' are the Young's modulus and Poisson's ratio of coating, $\phi_\parallel$ and $\phi_\perp$ are the mechanical loss values for the coating for strains parallel and perpendicular to the coating surface, d is the coating thickness and w_0 is the laser beam waist.

To estimate the thermal noise associated with this coating stack, it is necessary to first estimate the mechanical loss of the stack. This can be calculated as a weighted (by thickness and by stiffness/Young's modulus) average of the loss of the individual coating materials as shown in Eqs. (3) and (2) [13]. To calculate the loss of the 38 layers in the SiO_2/Ta_2O_5 coating stack and of the 26 layers in the $SiO_2/Ta_2O_5/aSi$ multimaterial stack the loss values given in Table II were used:

$$Y_{\text{coating}} = \frac{Y_{SiO_2}t_{SiO_2} + Y_{Ta_2O_5}t_{Ta_2O_5}(+Y_{aSi}t_{aSi})}{t_{SiO_2}+t_{Ta_2O_5}(+t_{aSi})} \quad (2)$$

$$\phi_{\text{coating}} = \frac{Y_{SiO_2}t_{SiO_2}\phi_{SiO_2} + Y_{Ta_2O_5}t_{Ta_2O_5}\phi_{Ta_2O_5}}{Y_{\text{coating}}t_{\text{coating}}} \times \left(+\frac{Y_{Si}t_{aSi}\phi_{aSi}}{Y_{\text{coating}}t_{\text{coating}}}\right) \quad (3)$$

Equation (3) gives the total loss ϕ_{coating} which is composed of the loss of different materials, while Eq. (2) allows the Young's modulus of the components to be calculated [14]. The thickness per material used for the calculations can be found in Table I. The results for the loss are summarized in Table II. While at room temperature (RT) the loss for the multimaterial stack is slightly higher than for the SiO_2/Ta_2O_5 stack, at lower temperatures due to the decreasing aSi loss the loss of the multimaterial stack becomes lower. This results in a reduction of Brownian thermal noise which was calculated using Eq. (1). The results are also given in Table II and represented by the black dots in Fig. 3. This approximation is in good agreement with the more precise model used in [9] with discrepancies of less than 5%. Figure 3 also shows the Brownian thermal noise for the SiO_2/Ta_2O_5 (lines) coating and the multimaterial coating (crosses and pluses) at RT (red, upper two curves) and at 20 K (green, lower two curves) calculated from the model used in [9].

TABLE II. Loss ϕ for SiO_2, Ta_2O_5 and aSi, and resulting loss for a SiO_2/Ta_2O_5 stack and the multimaterial stack each at room temperature (RT), 120, 20 and 10 K. The resulting Brownian thermal noise for the two stacks at each temperature was calculated using Eq. (1).

	Loss $\phi \times 10^{-4}$					Brownian th. noise (100 Hz) $\times 10^{-21}$	
	SiO_2	aSi	Ta_2O_5	SiO_2/Ta_2O_5	Multimat.	SiO_2/Ta_2O_5	Multimat.
290 K	0.4 [15]	4.0 [16]	2.3 [15]	1.26	1.62	4.9	4.3
120 K	1.7 [6]	0.5 [16]	3.3 [17]	2.58	2.1	4.5	3.5
20 K	7.8 [6]	0.4 [16]	8.6 [17]	8.24	6.98	3.4	2.6
10 K	7 [6]	0.3 [16]	6 [17]	6.46	5.64	2.2	1.7

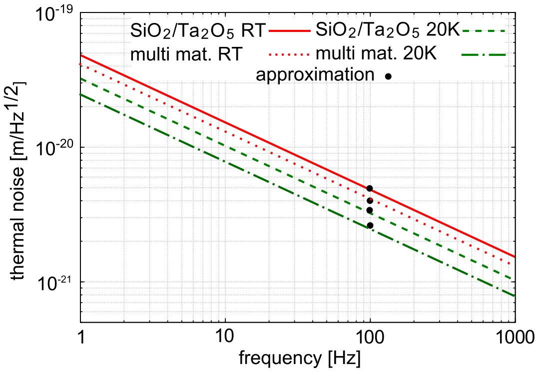

FIG. 3 (color online). Brownian thermal noise for the SiO_2/Ta_2O_5 coating at room temperature (red line) and at 20 K (dashed green line) and for the multimaterial coating at room temperature (dotted red line) and at 20 K (dash-dotted green line) calculated from the model used in [9]. The black dots show the corresponding results calculated with Eq. (1).

IV. OPTICAL ABSORPTION OF THE COATING STACK

To estimate the optical absorption of this multimaterial stack, we consider two experiments in which we measured the absorption of a SiO_2/Ta_2O_5 coating stack and an aSi/SiO_2 coating stack separately using *photothermal self-phase modulation* (PSM) [18]. In Sec. IV A we present measurements of the optical absorption of a SiO_2/Ta_2O_5 coating stack at 1550 nm for the first time, while in Sec. IV B a new aspect of the absorption results of an aSi/SiO_2 coating stack are discussed which were published in [8].

A. Silica/tantala

For the absorption measurement on SiO_2/Ta_2O_5 at 1550 nm a Fabry-Pérot cavity was used. The two cavity mirror substrates consisted of Corning 7980 glass [19]. The coatings were manufactured at *Advanced Thin Films* (ATF) [20] and were optimized for a finesse of 10 000 at an angle of incidence (AOI) of 0° at 1550 nm. A finesse of 10 000 theoretically is reached by two identical lossless mirrors with intensity reflectivity of $R_1 = R_2 = 99.969\%$ (1-R = 310 ppm). The transmission measured by the manufacturer on a mirror from this coating run was T = 320 ppm.

1. Experimental setup

For the Fabry-Pérot cavity setup, two identical curved mirrors M_1 and M_2 were clamped facing each other, separated only by a 0.75 mm viton seal. A Piezo electric transducer (PZT), driven by a function generator (FG), presses M_2 into the viton seal and therefore changes the cavity length. Both mirrors have a concave radius of curvature (ROC) of 0.5 m resulting in a cavity waist of $w_0 = 82\ \mu$m. The short cavity length results in a large free spectral range (FSR) of 200 GHz. The material properties and cavity geometry parameters of this setup are summarized in Table III.

To linearize the mirror motion, the cavity length was modulated only in a small range around the resonance of approximately 0.3% of a FSR: this range varied slightly with the modulation frequency (the modulation voltage was constant for all measurements). The actual mirror motion for each modulation frequency and expansion and contraction of the PZT in each case was calibrated using side bands imprinted on the laser signal via an electro-optical modulator (EOM) before entering the cavity; for details see [23]. The resonance peaks for the absorption measurement were detected with a photodetector (PD) in reflection of input mirror M_1. The reflected beam was separated from the incoming beam at a polarizing beam splitter cube (PBS) using a $\lambda/2$ wave plate and a Faraday rotator.

2. Results

Resonance peaks detected at fast scan frequency or low power show no thermal effect (resonance peaks identical for lengthening and shortening of the cavity). Such measurements allow a determination of the reflectivity R_1 of the input mirror M_1 and the effective reflectivity $\tilde{R}_2$ of M_2 which contains all round-trip losses. Assuming $R_1 = R_2$, the cavity round-trip loss is $\tilde{R}_2 - R_1$. A reduction of the scan frequency and a power increase cause a thermal effect (resonance peaks are different for lengthening and shortening of the cavity as shown in Fig. 4(a). These measurement additionally allow the determination of the absorption coefficient M_1. To measure the absorption, several single measurements of reflected resonance peaks were detected, partly showing a thermal effect, partly showing no thermal

TABLE III. Material and geometric parameters of the Corning 7980 mirror substrates and the cavity, as used for the simulations. Wavelength and temperature dependent parameters are given at 1550 nm and room temperature.

Material parameters		Ref.	Cavity geometry parameters	
Index of refraction n	1.44	[21]	Input power P	2, 130, 260 mW
Thermo refr. coeff. dn/dT	9.6×10^{-6}/K	[19]	Length L	0.75 mm
Specific heat c	770 J/(kg K)	[22]	Beam waist w_0	82 μm
Density ρ	2201 kg/m^3	[19]	Mirror thickness D	6.35 mm
Thermal expansion a_{th}	0.52×10^{-6}/K	[19]	Angle of incid. (AOI)	0°
Thermal conductivity k_{th}	1.3 W/(m K)	[19]		

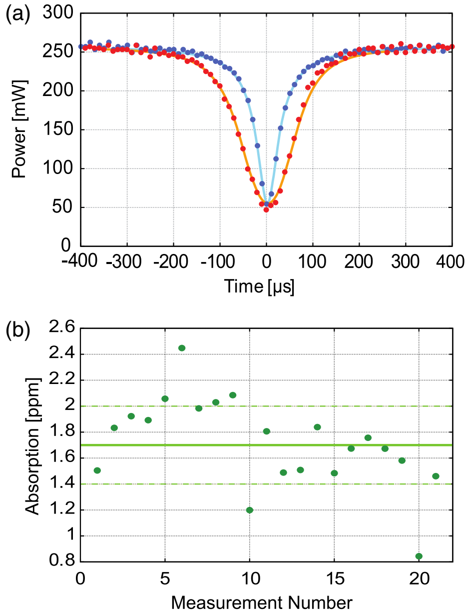

FIG. 4 (color online). Measurement results for tantala HR coatings at 1550 nm. (a) An example of deformed resonance peaks from which the coating absorption was calculated. For an external lengthening of the cavity the resonance peak is broadened (simulation: orange line, measurement: red dots) while for an external shortening of the cavity the peak is narrowed (simulation: light blue line, measurement: dark blue dots). (b) The results for the absorption of the single measurements (dark-green dots). The light-green line and dashed lines mark the mean value and standard deviation of $\alpha = (1.7 \pm 0.3)$ ppm.

effect. The measured peaks were fitted as described in [24] with the input parameters shown in Table III.

Altogether 34 single measurements were performed, 21 showing a significant thermal effect. The results for the reflectivities were $1 - R_1 = (253.73 \pm 16.4)$ ppm and $1 - \tilde{R}_2 = (276.3 \pm 13.3)$ ppm, resulting in a cavity finesse of $F = (11853 \pm 704)$ which was slightly higher than specified.

The results of the single measurements are shown in Fig. 4(b), the light-green bar marking the mean value of the 21 single results, and the dashed light-green bars their standard deviation. The resulting absorption for the input mirror coating is $\alpha = (1.7 \pm 0.3)$ ppm (0.3 ppm $\hat{=}$ 17.6% of α). This is a promising low result for the optical absorption of SiO_2/Ta_2O_5 at 1550 nm and, considering the thicker quarter wave layers due to the longer wavelength, in good agreement with absorption values at 1064 nm. (Note that this coating stack was not specified particularly for low absorption. Therefore, further absorption reduction might be possible.)

3. Error propagation

For a detailed discussion of the possible error caused by the input parameters see [23], where the expected error due to inaccurate material properties is analyzed. Since the material properties are identical or at least very similar to the parameters discussed in [23], their influence on the result also is very similar. The mirror dimensions are also identical to the experiment in [23]; input power and mode matching always influence the result approximately linearly. The only parameters which differ strongly from the other experiment are the cavity length and the beam waist. These two parameters were changed each by $\pm 10\%$ and the results of one single measurement were recalculated. An error of $\pm 10\%$ in the cavity length influences the result by approximately $\pm 10\%$, where a cavity length assumed too long reduces the necessary absorption for the present thermal effect and inverse for a cavity length assumed too short. An error in the cavity length also affects the waist. An error of $\pm 10\%$ in the length only affects the waist by approximately $\pm 3\%$, which causes an error of $\pm 6\%$ in the absorption result. The large error of about 10% for such a short cavity is realistic. Since cavity length and waist depend on each other as discussed, both errors add. The summed-up error is still within the standard deviation for the absorption result.

Therefore for the results obtained from this series of measurements the standard deviation caused by statistical fluctuations of the detected resonance peaks is assumed to dominate the error caused by inaccurate input parameters.

B. aSilicon/silica

Results as well as experimental details for the optical absorption of aSi/SiO_2 coatings measured with PSM were published in [8]. The coatings were produced by *Tafelmaier* using *ion plating* [25]. In this experiment, the cavity consisted of three mirrors. The input and output mirrors M_1 and M_2 were identical and reflected the laser beam at an AOI of 42°, while the third mirror M_3 was highly reflective (transmission negligible) at an AOI of 3°. The optical absorption of the input mirror of the aSi/SiO_2 cavity was $\alpha_{M_{1,p-pol}} = (1428 \pm 97)$ ppm for p-polarization and $\alpha_{M_{1,s-pol}} = (1035 \pm 42)$ ppm for s-polarization. The difference in absorption for the two polarizations originates from the difference in reflectivity and therefore different penetration depth of the incident laser beam into the coating stack. Considering a reduction of the laser light due to SiO_2/Ta_2O_5 bilayers to 0.35%, in s-polarization 3.6 ppm of the input laser light would be absorbed (and 5 ppm in p-polarization) which is in the same order as the absorption of SiO_2/Ta_2O_5 coatings.

It was observed before that the optical absorption of dielectric coating stacks at a large AOI can be significantly higher than at 0°. (For a SiO_2/Ta_2O_5 coating stack at an AOI of 42°, in [24] a rather high absorption of 23 ppm was measured using PSM and confirmed independently with a calorimetric measurement while due to the manufacturer approximately 1 ppm was expected as demonstrated in [26].) Therefore, here we will discuss the optical absorption

TABLE IV. Results for the optical absorption α, input mirror reflectivity R_1, and effective output reflectivity $\tilde{R}_2$ [includes all optical round-trip loss apart from (1-R_1)], resulting in an upper limit for the optical absorption $\alpha_{M_3} = R_1 - \tilde{R}_2 - 2 \times \alpha_1$ of M_3.

Parameter	Result s-pol	Result p-pol
1-R_1 (ppm)	529 ± 20	4717 ± 212
$1 - \tilde{R}_2$ (ppm)	2902 ± 103	7882 ± 251
α_{M_1} $(= \alpha_{M_2})$ (ppm)	1035 ± 42	1428 ± 97
α_{M_3} (ppm)	303 ± 207	$309 + 657/-309$

of mirror M_3 which reflects almost at normal incidence from the cavity round-trip loss which is a result provided by PSM in addition to the measurement of the input mirror absorption. As M_1 and M_2 were coated in the same coating run, identically cleaned and then glued to a closed spacer in a clean room environment their absorption and reflectivity can be assumed to be identical, $\alpha_{M_1} = \alpha_{M_2}$ and $R_1 = R_2$. In s-pol the reflectivity of M_1 was found to be $1 - R_1 = (529 \pm 20)$ ppm. The effective reflectivity of the output mirror was $1 - \tilde{R}_2 = (2902 \pm 103)$ ppm where $\tilde{R}_2$ includes the transmission of M_2 as well as the absorption of all three mirrors. Considering known transmission and absorptions, for M_3 an upper limit for the absorption of $R_1 - \tilde{R}_2 - 2 \times \alpha_{M_{3,s-pol}} = (303 \pm 207)$ ppm remains. Equivalently, for p-polarization where the reflectivities were $1 - R_1 = (4717 \pm 212)$ ppm and $1 - \tilde{R}_2 = (7882 \pm 251)$ ppm the upper limit for M_3 absorption is $\alpha_{M_{3,p-pol}} = (309 + 657/-309)$ ppm. An absorption of $(309 + 303)/2 = 306$ ppm for a highly reflective aSi/SiO_2 coating stack at an AOI close to 0° is an even more promising result for aSi/SiO_2 coatings. The absorption of the incident laser beam would be reduced to 1.1 ppm by the upper SiO_2/Ta_2O_5 layers. All values are summarized in Table IV.

V. DISCUSSION AND CONCLUSION

In our model we replaced 11 bilayers of SiO_2/Ta_2O_5 by 5 bilayers of aSi/SiO_2 resulting in 26 instead of 38 single layers in total. Due to the high refractive index of $n_{Si} = 3.5$ of the aSi layers, using the multimaterial stack can achieve the same high reflectivity of $T \approx 0.5$ ppm while the total thickness is reduced from 8.684 μm to 5.701 μm by 34%.

Due to reducing the number of bilayers and replacing a part of the Ta_2O_5 layers by low loss aSi, the loss of the multimaterial stack at low temperatures reduces by about 20% at 120 K and 15% at 20 and 10 K. The Brownian thermal noise reduces by about 15% at RT and 25% at low temperatures.

In our model for a three material coating stack 100% of the laser power affects the top stack which is made of SiO_2/Ta_2O_5. So we can expect about (1.7 ± 0.3) ppm absorption in this part of such a coating. (The largest amount of absorption occurs in the first 2–3 bilayers of a coating stack. So the smaller number of layers compared to the experiment will not reduce the absorption significantly.) Only 0.35% of the laser power is transmitted into the aSi/SiO_2 part of the stack. This reduces the absorption of the input laser power to $0.0035 \times (1035 +/- 42)$ ppm $= (3.6 +/- 0.1)$ ppm. Therefore we conclude that a total optical absorption of as low as (5.3 ± 0.4) ppm can be achieved for such a three material based coating stack which is in the order of the coating absorption requirement of about 1 ppm of future GWDs.

For an AOI close to 0° from the cavity round-trip loss a lower absorption of 0.0035×306 ppm $= 1.1$ ppm was concluded for aSi/SiO_2 coatings which is promising for further absorption reduction.

The aSi in these coating stacks was not optimized to be low absorbing. Work on improving the optical absorption of such aSi layers provides the perspective to replace more Ta_2O_5 layers by aSi to further reduce Brownian thermal noise. In our design so far the SiO_2/Ta_2O_5 also was not explicitly optimized to have low absorption. Absorptions of less than 0.7 ppm at 1064 nm [27] suggest the possibility of further reducing the SiO_2/Ta_2O_5 absorption also at 1550 nm.

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