Journal of Nondestructive Evaluation

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--Manuscript Draft--

Manuscript Number:	
Full Title:	Ultrasonic characterization of subsurface 2D corrugation
Article Type:	Brief Communication
Keywords:	subsurface 2D corrugation; ultrasonic backscatter; Bragg regime; periodicity and symmetry characterization
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Abstract:	The ultrasonic backscattering technique is employed for the characterization of a (hidden) 2D surface corrugation which is superposed on a polycarbonate sample. Previous studies varied the incident angle at the symmetry orientations of the surface structure in order to extract the characteristic periodicities. Here, we additionally vary the orientation of the vertical insonification plane. As such the characteristic periodicities as well as the surface symmetries can be extracted without any prior knowledge of the surface structure. In addition, we apply this extended methodology to the investigation of a 2D subsurface corrugation. Although the diffraction conditions do not change in comparison with a visible 2D surface corrugation, some additional attention is required as the elastic properties of the substrate material put further restrictions to the range of applicable ultrasonic frequencies. The characterized periodicities and symmetries are in excellent agreement with the design parameters of the (hidden) 2D surface grating.

ULTRASONIC CHARACTERIZATION OF SUBSURFACE 2D CORRUGATION

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ABSTRACT

The ultrasonic backscattering technique is employed for the characterization of a 2D surface corrugation which is superposed on or hidden on the backside of a polycarbonate sample. In contrast to previous studies where the incident angle at well-defined and a-priori known symmetry orientations of the surface structure is varied in order to extract the characteristic periodicities, the backscatter polar scan method incorporates an additional variation of the orientation of the vertical insonification plane within the experimental measurement protocol. As such, the characteristic periodicities as well as the surface symmetries can be extracted without any prior knowledge of the surface structure. As a benefit compared to optical methods, we have also validated this extended methodology for the investigation of a 2D subsurface corrugation. Although the diffraction conditions do not change in comparison with a visible 2D surface corrugation, we remark that additional attention is required in the sense that the elastic properties of the substrate material put further restrictions to the range of applicable ultrasonic frequencies. The characterized periodicities and symmetries are in excellent agreement with the design parameters of the (hidden) 2D surface grating.

Keywords: subsurface 2D corrugation; ultrasonic backscatter; Bragg regime; periodicity and symmetry characterization.

I. INTRODUCTION

The deployment of periodic surface structures is indispensable for a variety of engineering applications, such as frequency filters, phononics, telecommunication, tailored sliding friction, etcetera. Several tools are available for inspecting and characterizing both random and periodic surface topography at different scales, among which include stylus profiling, electron waves, X-ray, optical waves and ultrasonic waves.

Within the last category, several studies have investigated both experimentally and numerically the interaction of a broadband ultrasonic wave, normally incident on a solid, with a surface structure. Subsequent analysis of the reflected or transmitted signal in the frequency domain then yields features which are linked to geometrical and mechanical properties of the investigated specimen [1; 2; 3; 4; 5]. In addition, as normal incidence analysis limits the range of obtainable information, the experimental and theoretical investigations have been extended to the use of oblique incidence, and applied to a variety of surface structures [6; 7; 8; 9; 10; 11; 12; 13; 14]. Since a periodic surface acts as a diffraction grating, its geometrical features can be extracted by analyzing the associated diffraction phenomena, most often, by operating in backscatter mode (Bragg regime). Doing so, a signal is only received at that angle, the Bragg angle, at which a diffracted component is scattered back to the emitter. Such a configuration is common in crystallography with X-rays [15], and is equally valid for ultrasonic waves.

Examples of the oblique incidence method described in literature all assume a-priori known symmetry lines of the surface grating under investigation. In references [10; 11], a narrowband ultrasonic transducer, positioned along the symmetry lines, was used to investigate both 1D and 2D (im)perfect surface structures. Recording of the backscattered intensity versus the grazing angle showed maxima, exposing the Bragg angles. The value of the Bragg angle was used to determine the periodicity, while the backscattering intensity was found to relate to the rms value of the surface roughness [10; 11]. In addition, the authors showed that the same set-up could be used to inspect an internal 1D grating [11]. By using a broadband pulse and a spectroscopic analysis of the backscattered wave, the incident angle can be fixed to some discrete values to obtain equivalent results [10]. In the work of Herbison [9; 12], several experiments have been performed on plates superposed with an imperfect 1D or 2D surface corrugation. By combining the spectroscopic approach with the scanning of the incident angle, an angular spectrogram is obtained. Here again, the axis of rotation of the transducer was aligned with either the principal axes or the diagonal of a surface unit cell. The recorded angular spectrogram exposed continuous Bragg scattering curves, from which the periodicity of the inspected surface structure was determined. The angular spectrograms further revealed amplitude variations, which have been explained by the appearance of backscattered leaky Lamb waves, as earlier observed in for example the work of Nagy [16]. Likewise, the method of angular spectroscopy has been further applied using air-coupled transducers to the inspection of 1D stacked cylindrical rods [17].

In the present study, we employ the polar scan methodology [18] in which the angular motion path of a narrow-banded immersion transducer is varied along two perpendicular angles, scanning the surface of the upper hemisphere, in order to characterize both periodicities and symmetry orientations without any prior knowledge of the surface structure. This is in strong contrast with the above mentioned studies which were limited to a fixed vertical insonification plane, thus implying that certain prior knowledge about the symmetry orientations of the surface structure is required to obtain the characteristic periodicities. Moreover, as shown in our experiments, the selection of particular vertical insonification planes entails that certain backscatter signals are left unrecorded in a real situation. In addition, we apply the polar scan methodology to the nondestructive evaluation and characterization of a subsurface 2D corrugation, and highlight several features that require special attention. The characterized periodicities and symmetries are in excellent agreement with the design parameters of the (hidden) 2D surface corrugation.

II. MATERIALS AND EXPERIMENTAL PROCEDURE

A 2D surface corrugation is applied to a polycarbonate (PC) sample (thickness $d = 1.1$mm) by ablating a predefined structure with an excimer laser. The 2D grating can be conceived as two overlapping 1D gratings (further called grating A and grating B), characterized by the periodicities $\Lambda_A = 250\mu$m and $\Lambda_B = 375\mu$m and with traces oriented along the in-plane angles $\Phi_A = 100°$, respectively $\Phi_B = 10°$ (see also Table 1). The power of the excimer laser is adjusted such that the ablated surface structure matches a designed depth of $D \approx 17\mu$m. The ablating process is performed in a controlled environment (temperature, pressure and humidity) in order to improve the quality of the surface structure.

The corrugated sample has been insonified by means of a piezoelectric ultrasonic immersion transducer (spatial width of 13mm) which is operated in the quasi-harmonic regime by exciting wave trains of at least 10 sine periods at frequency f = 5MHz. The immersion liquid is water, with a measured sound speed of $c = 1475.4 \pm 1.27$m/s. The distance between the transducer and the sample is kept constant at 65mm during the experiment, as such the experiment takes place in the far-field regime. The pulse repetition frequency is chosen sufficiently low to avoid overlapping signals and multiple reflections. A wide range of oblique incidence angles $\psi(\varphi,\theta)$ is considered, in which θ the angle with the normal on the sample and φ the in-plane polar angle. The incident angle θ ranges from -60° to +60° in steps of 0.05°, while the polar angle φ varies from 0° to 180° with

0.5° resolution. Angular position feedback is provided by high-precision encoders. To avoid any transient effects, the analysis is limited to the central part (with respect to the generated wave train) of the backscattered signal from which the amplitude value is stored for each incidence angle $\psi(\varphi,\theta)$.

III. RESULTS AND DISCUSSION

A. FRONT SIDE 2D GRATING

The experimental recording of the backscattered amplitude from a 2D grating located on the front surface is shown in Figure 1a. The incident angle θ is put on the radial axis, the in-plane polar angle φ on the angular axis, the color pigment represents the maximum amplitude (in arbitrary units) of the backscattered signal.

Several high-amplitude backscatter spikes can be observed in the experimental recording, each having a point-symmetric counterpart. Spike O corresponds to the specular reflection at normal incidence, and its position is used to compensate any angular misalignment during the experiment. The other spikes represent diffraction peaks and thus relate to the 2D surface structure. Spikes A, respectively B, correspond to -1st order diffraction peaks associated with grating A, respectively grating B. Spikes BB correspond to -2th order diffraction peaks associated to grating B. In addition, spikes with label A+B and A-B show up, which cannot be observed when limiting the investigation to the principal symmetry axis. At the currently used frequency of 5MHz, other higher order diffraction peaks, associated to grating A and/or grating B, could not be recorded within the angular range of the scanning apparatus. To do this, one could increase the ultrasonic frequency, however this is not considered here.

The polar angles φ of the backscatter spikes yield the symmetry orientations Φ of the grating according to

$$\Phi = \phi - 90^{\circ} \tag{1}$$

The periodicities Λ on the other hand are encrypted in the incident angle θ of the backscatter spikes according to the Bragg relationship for backscatter geometry [15]

$$\Lambda = \frac{m\lambda}{2\sin\theta} \tag{2}$$

with m the diffraction order (integer) and λ the ultrasonic wave length in water. Obviously, the appearance of diffraction peaks requires that the selected ultrasonic frequency matches at least the Bragg law with $m = 1$. In this case, it requires that $f > 2.96$MHz for the PC specimen.

Spikes (A+B), respectively spikes (A-B), are diffraction spikes associated to both grating A and grating B by considering the addition, respectively subtraction of the reciprocal grating parameters. The orientation $\Phi_{A\pm B}$ of a joint diffraction spike thus corresponds to

$$\Phi_{A\pm B} = \tan^{-1}\left(\frac{\left(\frac{1}{\Lambda_A}\sin\left(\Phi_A\right)\mp\frac{1}{\Lambda_B}\sin\left(\Phi_B\right)\right)}{\left(\frac{1}{\Lambda_A}\cos\left(\Phi_A\right)\mp\frac{1}{\Lambda_B}\cos\left(\Phi_B\right)\right)}\right)\pm 90 \tag{3}$$

while its associated periodicity $\Lambda_{A\pm B}$ can be written as

$$\Lambda_{A\pm B} = \left(\sqrt{\frac{1}{\Lambda_A{}^2}+\frac{1}{\Lambda_B{}^2}-2\frac{\cos\left(\Phi_B-\Phi_A\right)}{\Lambda_A\Lambda_B}}\right)^{-1} \tag{4}$$

Hence, evaluation of the different experimental backscatter peaks within the polar scan yields the in-plane surface parameters (both symmetry orientation and periodicity) of the 2D surface structure. The accuracy and reproducibility of the extracted grating parameters depends on the precision with which the spike locations can be determined. In fact, the two main complicating factors are: the smearing of the experimentally recorded peaks due to the angular frequency content of the employed transducer, and the presence of experimental noise. To obtain a robust analysis, the experimental recording has been first convolved by a Gaussian kernel being representative for the amplitude distribution of the employed ultrasonic wave. The subsequently extracted surface parameters (and their relative error) are listed in Table 1, and show good agreement with the design parameters.

B. BACKSIDE 2D GRATING

Ultrasonic waves are well-known for their excellent penetration capabilities inside solid materials, at least when insonified at normal incidence. In this section, we consider the case when the 2D surface grating is located at the backside of the PC sample. The backscatter polar scan recording is shown in Figure 1b. The similarity with the front-side backscatter recording discussed in previous section (see Figure 1a) is obvious, and is easily understood by recalling Snell-Descartes' law which states that the horizontal component of the incident wave vector is conserved. As such, the diffraction conditions remain unchanged, even though mode conversion may occur [19], and the recorded diffraction peaks do not change location when the 2D grating is located at the backside. The only remarkable change in the polar scan image is that the amplitude value of the backscatter signal is significantly lower at the diffraction peaks (with the exception at normal incidence). This is not surprising as the involved ultrasonic waves, incident at oblique angles, have to traverse the PC sample twice before being backscattered to the emitter/receiver. Additionally, we remark that the 1st order spikes A along $\varphi \approx 10°$ show a more drastic drop in amplitude level compared to the 1st order spikes B along $\varphi \approx 100°$. Even more, the 2th order spikes BB along $\varphi \approx 100°$ cannot be discerned anymore. Based on the visible diffraction peaks, the extracted corrugation parameters for the hidden 2D grating are added to Table 1. Again good agreement is obtained.

As the 2th order diffraction peaks could not be cut off by any critical angle phenomena (the PC sample has only one critical angle for the longitudinal wave, $\theta_{crit} = \sin^{-1}(1475.4/2270) \approx 40.5^{\circ}$ [20]), we have performed a conventional polar scan transmission experiment to investigate the coupling efficiency and transparency constraints of the PC sample. The recorded transmission amplitude characteristics of the corrugated PC sample at f = 5MHz are displayed in Figure 2a. At first glance, the amplitude map shows circular symmetry, indicating the mechanical isotropy of the PC sample [21]. Close observation, however, reveals small deviations in the circular amplitude distribution (best seen for large incident angles θ). It has been experimentally verified in our lab that the slight distortion of the circular symmetry has to be attributed to the presence of the surface structure. Taking into account the current parameters, i.e. frequency f and thickness d, it was found that bulk wave propagation is most dominant within the PC solid. The critical angle for the longitudinal wave is reflected in the transmission amplitude dip at $\theta = 41.6°$ (which is in good agreement with the above calculated value of 40.5°). The amplitude map further reveals a transmission transparent window (longitudinal dominated coupling) for $\theta < 41.6°$, while at larger incident angle θ (shear dominated coupling) the transmission coefficient tends to zero. This implies that, although the diffraction conditions prescribed by Bragg's law remain unchanged, a proper characterization of the in-plane parameters of the subsurface grating demands a lower limit for the ultrasonic frequency f such that the 1st order diffraction peaks are located within the transparent transmission window. For the PC sample considered here, this leads to the condition that $f > 4.45$MHz. Obviously, for other substrates this frequency limit shifts depending on the elastic properties.

In contrast to the elasticity independent diffraction conditions, expressed by means of the Bragg angles, the amplitudes of the diffraction peaks are clearly dependent on the substrate material characteristics. Hence, the extraction of the height parameters of a subsurface structure cannot be simply done by solely evaluating the recorded backscatter intensities. Furthermore, we note that the mode conversion process in refraction at the upper liquid-solid interface inhibits the inspection of a local spot at the back surface therefore limiting the usability of the present backscatter technique to characterization of subsurface structures having spatially uniform in-plane parameters. The above observations become even more important in case of inspecting a subsurface grating superimposed on anisotropic elastic substrates as the transmission characteristics of anisotropic media display a more complex shape (see Figure 2b for a cross-ply carbon/epoxy laminate) in which multiple (non-)transparent transmission windows are observed. In addition, wave propagation in an anisotropic solid does not necessarily take place within the insonification plane [19] making the interpretation of backscattered sound, originating at the bottom surface, impossible without profound knowledge of the material characteristics.

IV. CONCLUSIONS

The in-plane parameters of a (hidden) 2D surface grating superimposed on a polycarbonate sample have been ultrasonically characterized by evaluating the backscattered amplitudes for a wide range of oblique incident and polar angles. Good agreement with design parameters is obtained. In addition, it is shown that proper characterization of the subsurface 2D grating requires an ultrasonic frequency which does not only comply with Bragg's law, but also matches a constraint based on the substrate material characteristics. This constraint further implies that the usability of the backscatter technique is only assured for characterizing spatially uniform subsurface corrugations, and that its extension for subsurface grating detection inside anisotropic media becomes cumbersome.

V. ACKNOWLEDGEMENTS

Mathias Kersemans acknowledges funding of the FWO-Vlaanderen through grant G012010N. The authors are highly indebted to the Centre for MicroSystems Technology CMST (Ghent University) for supplying the PC sample.

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Figure captions

Figure 1: Backscatter amplitude map (f = 5MHz) for a 2D grating located at: (a) front surface (visible) and (b) back surface (hidden).

Figure 2: Transmitted amplitude, recorded at f = 5MHz: isotropic PC sample (a) and anisotropic $[0,90]_S$ carbon/epoxy laminate (b).

Table caption

Table 1: The first row "CMST" corresponds to the in-plane design parameters of the 2D grating. Rows "FRONT" and "BACK" correspond to the ultrasonically extracted parameters.

Figure1: Backscatter maps of (sub)surface 2D grating

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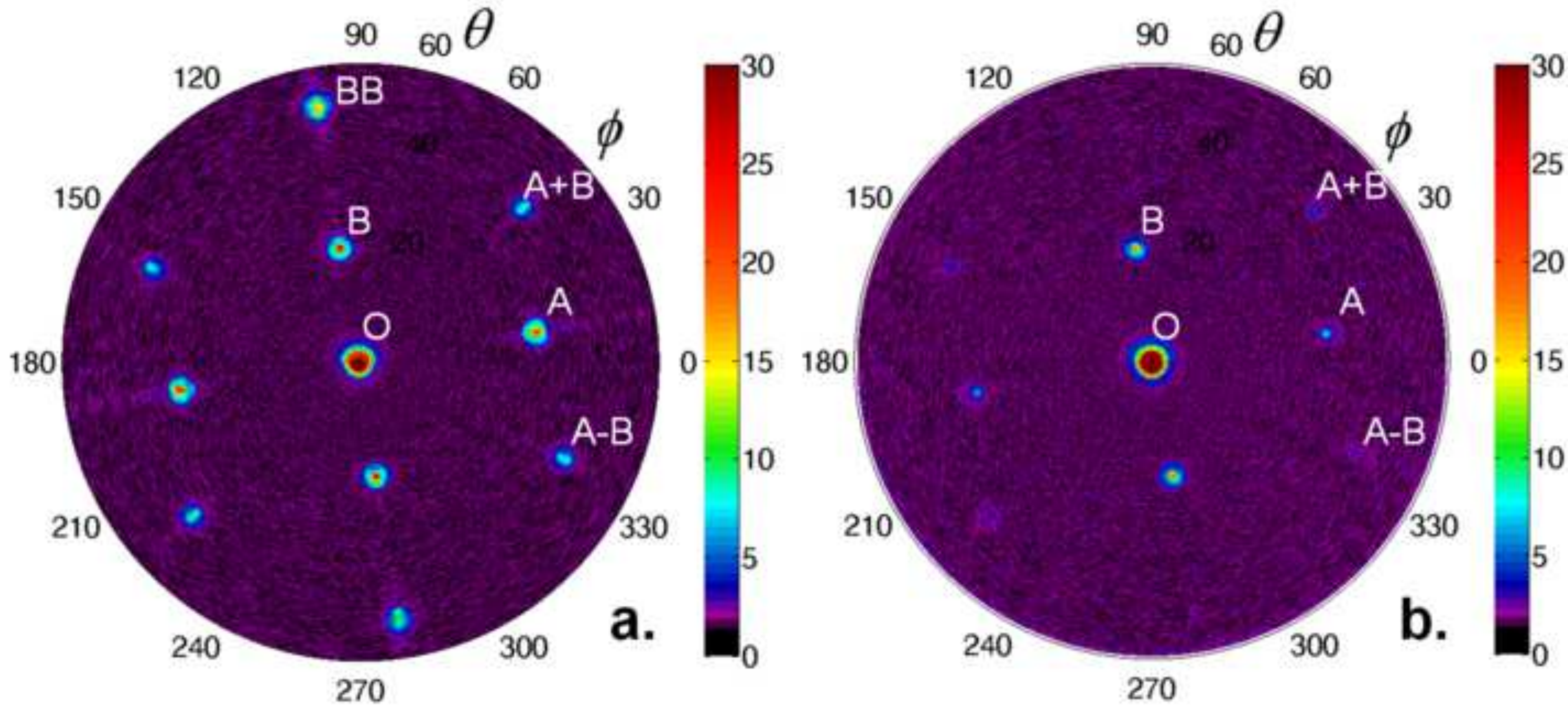

Figure2: Transmission characteristics
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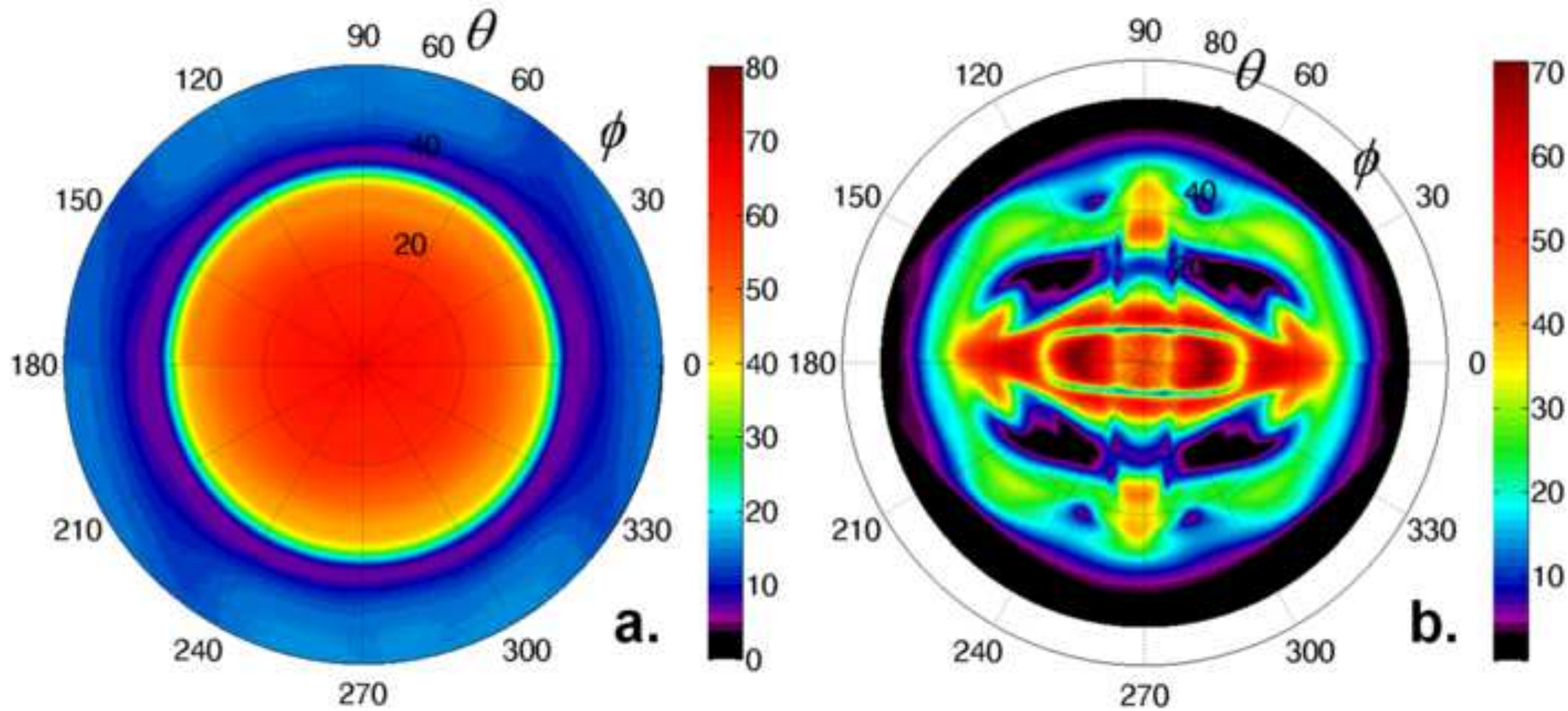

Table1: Characterized surface parameters

Table 1: The first row "CMST" corresponds to the in-plane design parameters of the 2D grating. Rows "FRONT" and "BACK" correspond to the ultrasonically extracted parameters.

	Λ_A [µm]	Φ_A [°]	Λ_B [µm]	Φ_B [°]	Λ_{BB} [µm]	Φ_{BB} [°]	Λ_{A+B} [µm]	Φ_{A+B} [°]	Λ_{A-B} [µm]	Φ_{A-B} [°]
CMST	250	100	375	10	375	10	208.0	43.7	208.0	-23.7
FRONT	249.8 -0.08%	99.3 -0.7°	375.3 +0.08%	9.0 -1°	374.7 -0.08%	9.1 -0.9°	208.3 +0.14%	42.9 -0.8°	209.3 +0.63%	-24.9 -1.2°
BACK	251.4 +0.56%	99.6 -0.4°	374.7 -0.08%	9.3 -0.7°	/	/	208.9 +0.43%	44.5 +0.8°	208.4 +0.19%	-24.7 -1°