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Research Article

Wide-band resonance reflectors for the visible spectrum

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Abstract

We present wide-band resonance waveguide reflectors at the visible wavelengths providing nearly 100% reflectance over a range of several tens of nanometres. The reflectors are based on multilayer designs consisting of layers of high and low index materials with a binary grating etched through the stack. We also fabricated an example structure and discuss the fabrication aspects of these elements.

Keywords: diffraction gratings; guided waves; resonance domain; subwavelength structures.

OCIS Codes: (050.1950) diffraction gratings; (130.2790) guided waves; (050.5745) resonance domain; (050.6624) subwavelength structures.

1. Introduction

Subwavelength structures that exhibit resonance effects [1–3] are employed in several applications including filters [4, 5], biosensors [6], pulse-shapers [7], second-harmonic generation [8], and field enhancement of fluorescence [9, 10]. Recently, it has been demonstrated theoretically [11–13] and experimentally [14–19] that with suitable structures the bandwidth of these resonance waveguide gratings (RWGs) can be stretched over a substantially wide spectrum. These wide-band RWG structures operate in the IR region, because to achieve a wide bandwidth the materials must possess high refractive index with negligible absorption. These conditions are quite easily fulfilled in the infrared region by making use of semiconductor materials such as silicon or germanium.

In the visible region of the spectrum many high refractive index materials are not transparent at least at the shorter wavelengths. However, there are some materials, such as atomic layer deposited (ALD) amorphous titanium dioxide (TiO_2), which have a relatively high refractive index at the visible region of the spectrum [20]. In fact, it has already been demonstrated that ALD TiO_2 can be used to obtain wider reflectance bands with high efficiency than the conventional RWGs provide at the visible wavelengths [21]. In this paper, we present certain multilayer RWG structures based on ALD TiO_2, which reflect nearly 100% of the incident light over a range of several tens of nanometres in the visible spectrum but are still relatively easy to fabricate. For demonstration purposes, we fabricated and measured the response of an example RWG which shows good agreement with the theoretical predictions. These structures can be useful, for example, as wide-band laser mirrors at the visible wavelengths.

The paper is organised as follows. The design of the RWGs is presented in Section 2 and the fabrication of the example structure is discussed in detail in Section 3. The measurements and the comparison of the results with the theoretical calculations as well as the problems encountered in the fabrication and characterisation are discussed in Section 4. Conclusions are presented in Section 5.

2. Design

There are many possible multilayer designs that can be used to obtain wideband reflectance with a flat band (see, e.g., ref. [13]), but in practice these structures are rather difficult to realise. If the fabrication process includes subsequent etching steps, the possibility of fabrication errors may lead to difficulties because the RWGs are very sensitive to the dimensional parameters.

In this paper, we apply a simple approach which contains only a couple of fabrication steps which are explained in detail in the next section. The structure consists of a multilayer stack with a binary grating etched through all layers. For example, a three layer TiO_2-Al_2O_3-TiO_2 structure, or alternatively a TiO_2-SiO_2-TiO_2 structure, gives a flat band almost over a hundred nanometres. Searching of the proper grating parameters can be done with rigorous electromagnetic theories and optimisation techniques. In this work, we used the Fourier modal method [22] together with the Simplex algorithm [23]. Figure 1A illustrates the reflectance of the optimised three-layer structure with the Al_2O_3 layer as a function of wavelength where the grating period is 301 nm, the heights of the layers are 158 nm, 235 nm, and 257 nm from top to bottom, respectively, and the fill factor $f=c/d$ is 0.58 (Figure 1B). The reflectance of this structure is nearly 100% at normal incidence from 460 nm to 550 nm in transverse magnetic (TM) polarisation, as can be seen in Figure 1A.

The above structures are realisable because they include only one etching step and the stack is easily deposited with a high degree of accuracy by using the ALD technique. However, in our case the fabrication of the three-layer structure was problematic because the adhesion between the TiO_2 and Al_2O_3

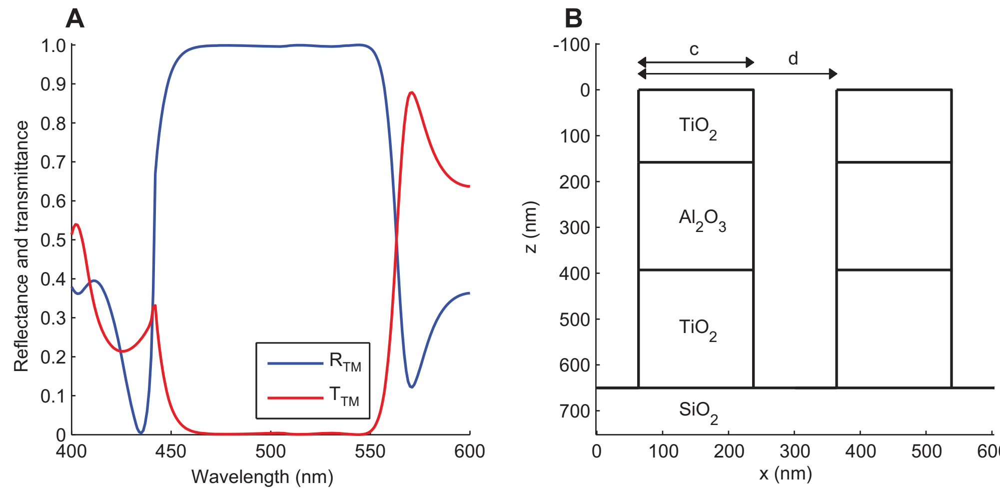

Figure 1 (A) Reflectance R_{TM} and transmittance T_{TM} of the three-layer TiO_2-Al_2O_3-TiO_2 RWG at normal incidence in TM polarisation. (B) The dimensions of the three-layer RWG. The fill factor is defined as the ratio *c/d* where *d* is the period of the grating.

layers was not good enough. Furthermore, because of the lack of a suitable precursor, we were not able to replace the Al_2O_3 layer with the SiO_2 layer in the ALD process and therefore we decided to demonstrate the fabrication of the RWG by using a two-layer stack which contains only the layers of TiO_2 and SiO_2, as shown in Figure 2B. Optimisation of the parameters for the two-layer RWG structure gives a period of 307 nm, thicknesses of TiO_2 and SiO_2 layers of 210 nm and 217 nm, respectively, and a fill factor of 0.48. The reflectance of the above mentioned RWG at normal incidence in TM and transverse electric (TE) polarisations is shown in Figure 2A. The bandwidth is a half of the three-layer structure, approximately from 450 nm to 495 nm where the reflectance is nearly 100%.

3. Fabrication

The process flow for the fabrication of the element is shown in Figure 3. First, a 210-nm layer of TiO_2 was deposited on a SiO_2 substrate with a Beneq TFS 200 (Beneq Oy, Vantaa, Finland) atomic layer deposition machine at 120°C. The utilisation of ALD TiO_2 instead of evaporated TiO_2 is essential because ALD TiO_2 has a substantially higher refractive index. The ALD technique is also very accurate which is important especially in the fabrication of the structures operating in the resonance domain. Then, a 35-nm chromium (Kurt J. Lesker, Clairton, USA) layer was deposited with electron beam evaporation (Leyobold L560, Leyobold

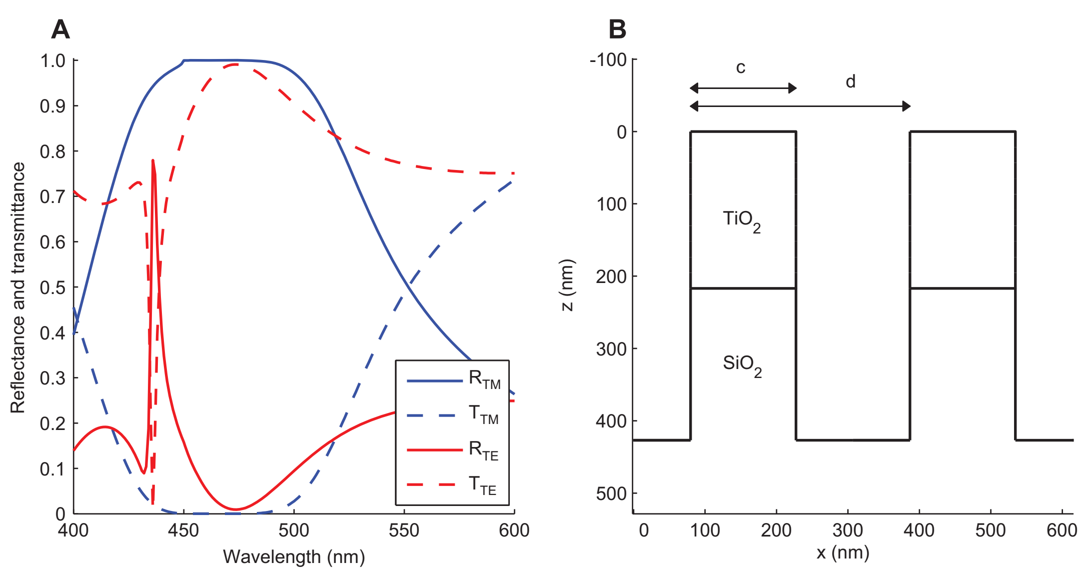

Figure 2 (A) Reflectance R and transmittance T of the two-layer TiO_2-SiO_2 RWG at normal incidence in TM and TE polarisations. (B) The design of the two-layer RWG. The fill factor is defined as the ratio *c/d* where *d* is the period of the grating. Note that only the zeroth order reflectance and transmittance are shown. The higher substrate orders start to emerge below the wavelength of 450 nm.

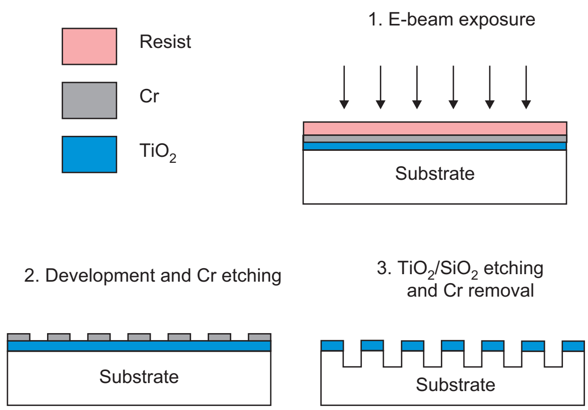

Figure 3 Process flow for fabricating the TiO_2-SiO_2 grating.

Heraeus GmbH, Hanau, Germany), and the grating pattern was exposed on a 180-nm layer of ZEP-7000 resist (Marubeni Corporation Japan, Osaka, Japan) with electron beam lithography (Vistec EBPG 5000+ES HR, Vistec Lithography, Cambridge, UK). After resist development, the metal mask for TiO_2 etching was fabricated by chlorine (Linde Gas Ab, Höllriegelskreuth, Germany) dry etching through the chromium layer (Plasmalab 100 ICP, Oxford Plasma Technology, Yatton, UK). Finally, the TiO_2 layer was dry etched with a Plasmalab 80+ (Oxford Plasma Technology, Yatton, UK) etching machine. The etching chemistry for TiO_2 was SF6/Ar (Oy AGA Ab, Espoo, Finland) (10/5 sccm, p=15 mTorr, RIE power 300 W). The same etching parameters were also used for SiO_2 etching with backside helium cooling. The final structure is shown in Figure 4. The refractive index of ALD TiO_2 used in the theoretical calculations of the RWGs is shown in Figure 5. The refractive index was measured from thin films with varying thicknesses using a variable angle scanning ellipsometer (VASE, J.A. Woollam Co. Inc., Lincoln, NE, USA).

4. Results

The fabricated element was characterised with a variable angle scanning ellipsometer by measuring the transmittance T at 0° incident angle as a function of wavelength for TE and TM polarised light. The reflectance R for each polarisation state was then solved from the relation R=1-T. At this point it should be noted that because the period is 307 nm and the substrate material is SiO_2, the ±1 diffraction orders start to emerge at the wavelengths below 450 nm in the transmission side. The designed flat band is above this cut-off wavelength, but as the profile of the fabricated grating is not perfect due to the slightly tilted side walls, as shown in Figure 4, the reflectance curve moves to the shorter wavelengths. Thus, the measured reflectance curve, shown in Figure 6, is not entirely correct at the wavelengths below the cut-off wavelength. The simulated reflectance, where the tilted side walls in the TiO_2 layer and the slight under etching of the SiO_2 layer have been taken into account, is also shown for comparison in Figure 6. We can see that some portion of the transmitted light goes into the ±1 orders and thus the real reflectance below the wavelength of 450 nm is slightly lower.

There are also other factors which can cause the differences between the measured and calculated values. From now on we consider only the TM polarisation which we are interested in. If either the realised refractive index of TiO_2 or the thicknesses of the TiO_2 layer differs from the optimised value, the reflectance drops below unity and the curve shifts in the wavelength axis. However, the thicknesses of the TiO_2 layer can be deposited very accurately using the ALD technique, and the measurement of the refractive index of TiO_2 was performed with several thin films with varying thickness. The deviation of ±5 nm in the TiO_2 layer, which is easily within the limits of ALD, still gives the reflectance above 99% for most of the reflectance band. The same holds also for the refractive index which can be approximately 2% lower than in Figure 5. Moreover, the simulations show that the reflectance is not sensitive to

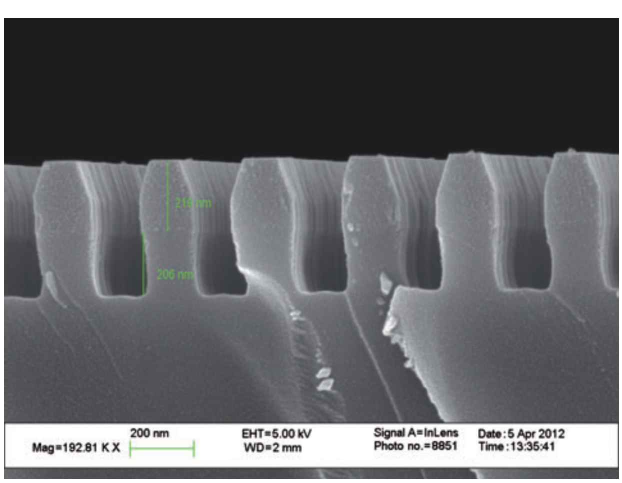

Figure 4 SEM image of the fabricated structure. The green bars denote the thicknesses of the TiO_2 and SiO_2 layers.

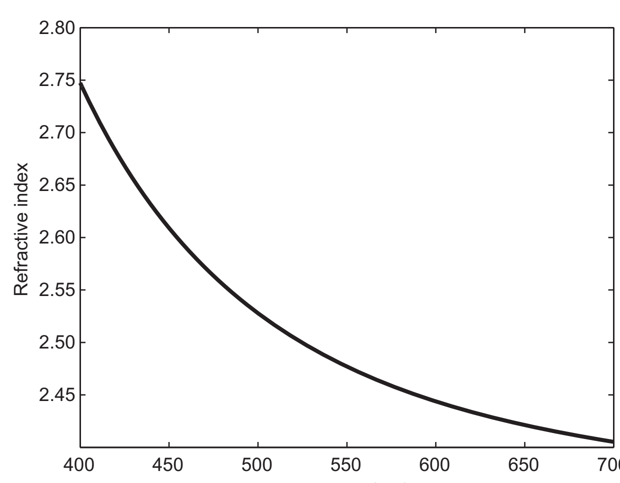

Figure 5 Refractive index of ALD TiO_2 as a function of wavelength.

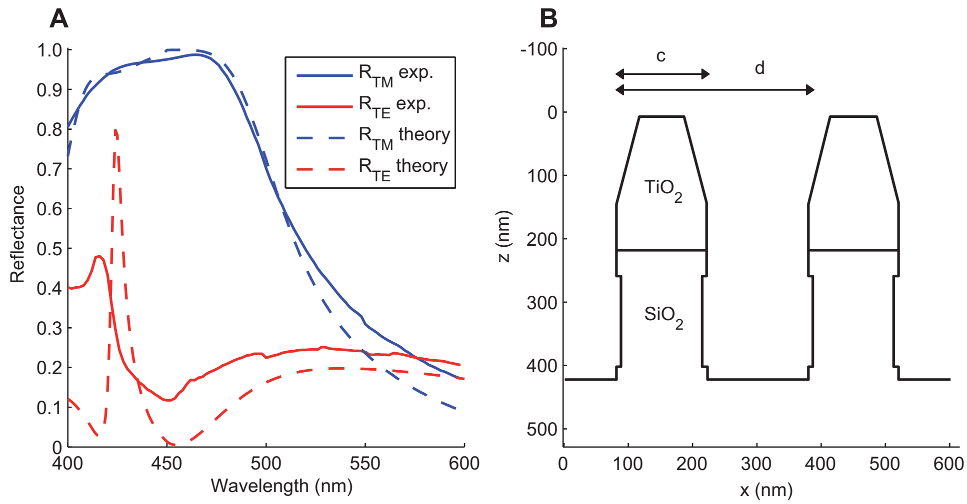

Figure 6 (A) Experimental reflectance curves (solid lines) determined from the measured transmittance of the zeroth order in TE and TM polarisations and the corresponding theoretical curves (dashed lines) where the tilted side walls have been taken into account. (B) Design of the two-layer RWG with the tilted side walls.

the thickness of the etched SiO_2 layer. In fact, even a 100-nm deeper SiO_2 layer gives almost identical reflectance.

The deviation in the fill factor and period also affect reflectance. The change of ±5 nm in the period still gives 99% reflectance but the curve again shifts slightly in the wavelength axes. This is not a problem with e-beam writing because the period can be controlled very accurately. The most critical parameter is the fill factor because the etching through two different materials can result in undesired changes in the line width. Again, to obtain 99% reflectance, the deviation in the fill factor can be approximately 2%. If the fill factor is approximately 10% smaller than the optimised value, the reflectance curve shifts to the shorter wavelengths in a similar manner as observed with the case of the tilted side walls shown in Figure 6. This confirms that the main reason for the discrepancy between the measured and calculated values is the tilted side walls in the TiO_2 layer, although the effect of the fill factor may also play a small part. Thus, by adjusting the etching process the measured results should approach theoretical predictions.

In the above discussion we considered TM polarisation only. The difference between the experimental and the theoretical reflectance curves in TE polarisation appears larger than in TM polarisation. The reason for this is that the TE reflectance peak is much narrower than the TM reflectance band and is therefore more sensitive to fabrication errors. This can be illustrated by considering an average of reflectance curves of several grating periods with small deviations in the parameters. Because each reflectance peak shifts slightly in the wavelength axis, the averaged reflectance peak is lower than the reflectance peak of a single grating with fixed parameters. The same does not occur in TM polarisation because of the wide reflectance band.

5. Conclusions

In this paper, we have presented RWG reflectors at the visible wavelengths providing nearly 100% reflectance over a range of several tens of nanometres. The reflectors are based on a stack of high and low index materials with a binary grating etched through the layers. We demonstrated the reflectors by fabricating a two-layer TiO_2-SiO_2 RWG using the ALD technique. Although there were some discrepancies between the theoretical and measured reflectance curves, we have shown that by a little adjustment of the etching process the reflectors are possible to realise in practice.

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