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Omnidirectional high-reflectivity mirror in the 4–20 μm spectral range

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Abstract

Decreasing-width multilayers (DWMs) can behave as highly-efficient broadband reflectors with wider reflection spectrum than periodic, disordered or other aperiodic structures made of the same materials. In this article, we numerically analyze and optimize the reflectance R of a linear DWM formed by the bilayer CsBr–Te from normal to grazing incidence and for a large wavelength spectrum (from mid to far infrared). As a result, when the rate of the thickness decrease of CsBr layers equals -59.5 nm/layer, an optimized average reflectance for p polarization $\langle R_p \rangle = 1 - 6 \times 10^{-6}$ can be obtained in the 4–20 μm spectral range for all angles of incidence. For s incident states, the average reflectance is even greater $\langle R_s \rangle = 1 - 3 \times 10^{-7}$. Moreover, a near-zero transmittance region $T \leqslant 10^{-12}$ occurs in the 12–20 μm wavelength interval constituting (to our knowledge) the widest spectrum for a single omnidirectional mirror where such remarkable reflectance values can be achieved.

Keywords: high-reflectivity mirrors, omnidirectional reflectors, aperiodic multilayers

(Some figures may appear in colour only in the online journal)

1. Introduction

The quest for a perfect reflector that allows truly omnidirectional reflection (ODR) for all polarizations over a wide selectable spectrum is a subject of ongoing research. These optical devices could be used in highly-desired applications including solar energy collection, protection of surfaces against high-power irradiation or creation of low-loss mirrors in laser cavities, among others. A great amount of research can be found in the literature reporting highly efficient reflectors over certain frequency ranges.

The most widely used devices consist of periodic multilayers with alternating layers of high and low refractive indices. Accordingly, the pioneering work by Fink *et al* [1] stated high reflectivity for TE and TM polarizations from 10 to 15 μm (at angles of incidence from 0° to 80°) in multilayer stacks composed of alternating micrometer-thick layers of polystyrene and tellurium. Photonic crystal devices based on thin film bilayers of TiO_2/SiO_2 [2] or Si/SiO_2 [3] have been designed to obtain ODR over the infrared spectrum. In the visible range, Deopura *et al* [4] described a highly efficient reflector formed by a stack of 19 alternating layers of tin (IV) sulfide and silica, while Lin *et al* [5] studied a highly efficient reflector with a 12-layer-pair stack of TiO_2/SiO_2. One-dimensional aperiodic multilayers can also behave as efficient mirrors in the visible, as recently reported by Barriuso *et al* [6] (generalized Fibonacci quasicrystals) or Bouazzi *et al* [7] (Triadic-Cantor structures). All these reflectors (periodic or aperiodic) combine high- and low-refractive-index layers where, to attain maximum reflectivity, the high refractive index should be larger than 2.26 and the corresponding low index similar to 1.5 [8].

Alternative high-reflectance devices with fewer number of layers are the triple-layer omnidirectional reflectors and the metamaterial monolayers. In this way, high reflectivities have been reported for all angles of incidence in the visible range

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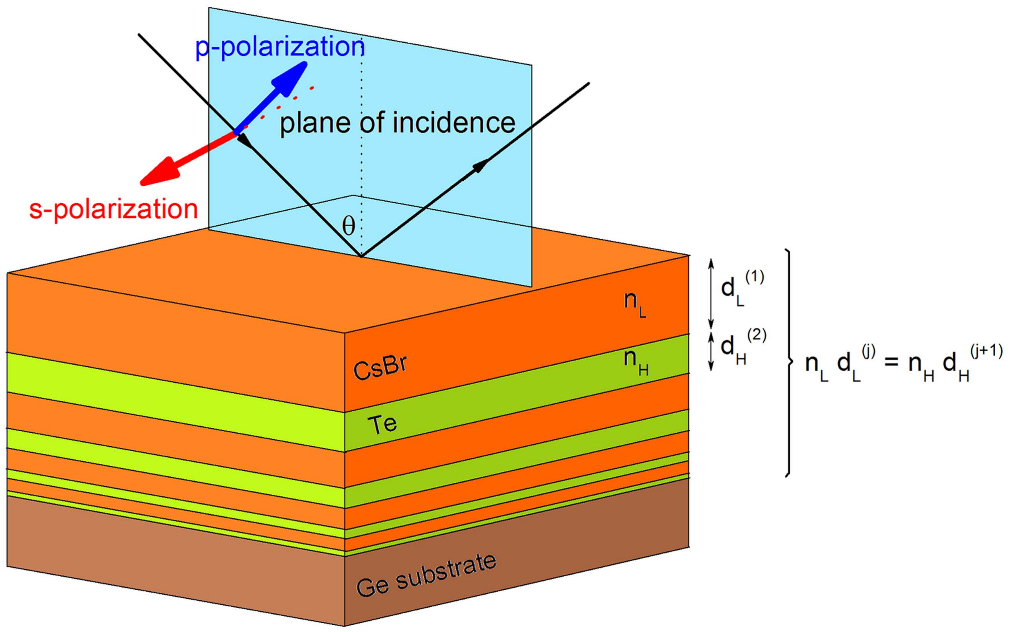

Figure 1. Our decreasing-width multilayer formed by N alternating isotropic layers with low n_L and high n_H refractive indices and initial widths $d_L^{(1)}$ and $d_H^{(2)}$, respectively. A 20 μm thick germanium (Ge) layer was chosen as the substrate. A light beam is incident on the structure at angle θ under both polarizations s and p (perpendicular and parallel to the plane of incidence, respectively).

Table 1. Sellmeier parameters in the 4–20 μm spectral range for CsBr and Ge.

	A_1	B_1	C_1	B_2	C_2	B_3	C_3
CsBr	1	0.953	0.008	0.830	0.027	2.847	14164.689
Ge	9.282	6.729	0.441	0.213	3870.100	0.0	0.0

for an ODR formed by a semiconductor, a quarter-wavelength transparent dielectric layer and a metal [9]. More recently, Lee *et al* [10] obtained a high reflectance over the ultraviolet (300–500 nm) in a sapphire/MgF_2/Al triple-layer and Liu *et al* [11] described average reflectances exceeding 98% from 1.261 to 1.533 μm with reflectors made from all-dielectric metamaterials. On the other hand, Moitra *et al* [12, 13] demonstrated an average reflectance over 98% across a 200 nm wide bandwidth in the infrared region for a silicon metamaterial monolayer, while Slovick *et al* [14] developed a 0.45 μm thick, silicon-based metamaterial monolayer with normal-incidence reflectivity over 99.999% at 1.5 μm. Another good candidate that might fulfill the requirements of ODR is a disordered system, essentially due to the fact of the localization of light [15]. The design of high-performance mirrors with a broader reflection band than periodic systems with the same refractive indices has been reported in [16–19].

In this article, we propose a decreasing-width multilayer (that is, a chirped structure or an aperiodic multilayer with a linear decrease of the layers' thickness) as a highly-efficient reflector over a remarkable wavelength spectrum (from 4 to 20 μm) and from normal to grazing incidence. Moreover, the aperiodic system achieves large average reflectance values for both s and p incident polarizations constituting, to our knowledge, the first single mirror to provide such significant reflectance values from mid to far infrared.

2. System description and numerical modeling

Our aperiodic multilayer is formed by N alternating isotropic layers with low n_L and high n_H refractive indices and initial widths $d_L^{(1)}$ and $d_H^{(2)}$, respectively (see figure 1). The thickness of the subsequent low-index layers follows a linear decrease with negative slope a_L:

$$d_L^{(j)} = d_L^{(1)} + a_L j \qquad \text{for } j = 3, 5, \ldots, N-1, \tag{2.1}$$

where the phase matching condition $n_L d_L^{(j)} = n_H d_H^{(j+1)}$ is satisfied (therefore, the high-index layers also obey a linear decrease imposed by the latter condition). We chose common semiconductor materials (caesium bromide, CsBr, for low-index layers and tellurium, Te, for high-index ones) with near-zero extinction coefficients over the entire 4–20 μm spectrum [20, 21]. Moreover, a 20 μm thick germanium (Ge) layer was selected as the substrate of the dielectric multilayer.

In relation to the refractive-index values for an incident wavelength λ, a Sellmeier-type dispersion equation was included in our numerical calculations:

$$n_i(\lambda) = \left[A_1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}\right]^{1/2} \quad \text{for } i = L, s, \tag{2.2}$$

where the corresponding parameters are shown in table 1 (all wavelengths in microns) and the subscript s stands for the Ge substrate. Regarding the refractive-index of the polycrystalline tellurium in the 4–20 μm transparency window, a value of $n_H = 5.3$ was chosen for our numerical calculations according to Popescu [22] (the monocrystalline tellurium birefringence disappears for Te thin films, as in our case). For completeness, the extinction coefficients κ of each material (within the transparency window) have been included in our model, leading to a complex refractive index for numerical computation. Thus, CsBr layers have extinction coefficients of about $\kappa_L \simeq 5 \times 10^{-6}$ for wavelengths in the 4–20 μm interval (see again [20, 21]) whereas for the Ge substrate, κ_s ranges from 10^{-7} to 2×10^{-4} in the same wavelength spectrum. Regarding the polycrystalline Te layers, the extinction coefficient is similar to the monocrystalline counterpart [22] where now $\kappa_H \simeq 2 \times 10^{-5}$ within the 4–20 μm spectral range.

Once modeled our decreasing-width multilayer (DWM), we numerically calculate its transmittance T with a Fortran 90 program code solving the transfer matrix equations [23]. It is worth mentioning that the parameter T implicitly contains the absorption term (due to the inclusion of the complex refractive indices in our model) so the relation $T = 1 - R$ holds, where R corresponds to the DWM reflectance.

3. Numerical results

First of all, let us compare the transmittance values T of our DWM with other periodic, aperiodic or disordered structures which have been reported as highly-efficient reflectors (maintaining similar total lengths). To this end, figure 2 shows contour plots for T versus the incident angle and wavelength. Five different structures formed by the bilayer CsBr–Te have been investigated for p-polarization where the Ge substrate thickness was chosen to be 20 μm, in all cases. Hence, in figure 2(a) we represent our numerical results for a DWM (48 layers) where $d_L^{(1)} = 3313.3$ nm and $d_H^{(2)} = 1037.7$ nm with a total length of 80 μm. The quarter-wavelength (QW) condition is fulfilled for this multilayer at 20 μm and the rate of thickness decrease for the CsBr layers corresponded to $a_L = -32.2$ nm/layer. It can be observed a near-zero transmittance domain (or, equivalently, a broadband high-reflectivity region) between 12 and 20 μm with higher transmittance values for lower wavelengths (an aspect that will be optimized shortly upon modifying the parameter a_L). In figure 2(b), a QW Fibonacci distribution of 9th generation (55 layers) was taken into account where now $d_L = 2530.1$ nm and $d_H = 792.5$ nm. The total length of this QW Fibonacci multilayer was 80 μm. In this case, the existence of low-transmittance bands is clear but with alternating resonant regions, being this aperiodic multilayer suitable as an excellent reflector over certain wavelength regions [6].

A QW triadic Cantor structure of 3rd generation with 27 layers is depicted in figure 2(c) ($d_L = 5400.0$ nm and $d_H = 1691.3$ nm) where its total length corresponded to 75.5 μm. Similarly to the Fibonacci structure, a number of reflection and transmission bands appear leading to a good reflector at specific spectra domain [7]. In addition, a QW periodic multilayer was numerically studied in figure 2(d) (38 layers) where the layers' thickness were chosen to be $d_L = 3222.9$ nm and $d_H = 1009.4$ nm with a total length of 80 μm. In this case, near-zero transmittance values (less than 10^{-12}) were achieved in the 16–20 μm range, apart from other wavelength intervals. Consequently, QW periodic multilayers constitute excellent reflectors (as it is well-known) but with narrower reflectance bands than aperiodic systems like the decreasing-width structures (compare again figures 2(a) and (d)). Finally, in figure 2(e), a disordered multilayer is analyzed (48 layers with a total length of 80 μm). In this case, the arrangement of layers has random boundaries, that is, we allow a total random variation of the layers' thickness (with a minimum of 100 nm up to 3 μm) where 500 disordered configurations have been taken into account for the averaging process. One notices a generalized average reflectance of $1 - 10^{-4}$ over the entire spectrum and for all incident angles. Nevertheless, the disordered multilayers's remarkable reflectance values are low if compared to DWMs or QW peridic structures in the same wavelength region.

Subsequently, from figure 2(a), it can be seen that decreasing-width mirrors behave as exceptional reflectors over significant wavelength regions. However, this only occurs for certain values of the parameter a_L, where average reflectances greater than $1 - 10^{-6}$ over the 4–20 μm range can be achieved (as we will show). For completeness, figure 3 (upper panels) shows the transmittance of our DWM versus the incident wavelength and angle (same number of layers and initial thickness as in figure 2(a)) for three different values of the decreasing rate a_L. A widening of the stop band (clearly noticeable between 4 and 20 μm) for increasing values of the parameter a_L appears, that is, as the aperiodicity of the multilayer becomes more pronounced, better reflectance values are obtained. After this, a question arises naturally: can the reflectance of our DWM be optimized in terms of the aperiodicity parameter a_L? The answer is depicted in figure 3 (bottom panel) where we represent the average transmittance $\langle T \rangle$ (over the entire spectrum and incident angles) as a function of the modulus of $|a_L|$. The periodic case (where $a_L = 0$) is also exhibited where, as expected, high average transmittance values are recovered. Moreover, when the aperiodicity parameter $|a_L| \geqslant 70.5$ nm/layer no DWM exists due to the negativeness of the layers' thickness values (just bear in mind that the decreasing rate a_L is negative). In the interval $0 \leqslant |a_L| < 70.5$ nm/layer, the average $\langle T \rangle$ is depicted for both s and p polarizations, where the average transmittance corresponding to upper panels (labeled as (a), (b) and (c)) is also presented. One observes a diminishing of the parameter $\langle T \rangle$ up to $|a_L| \simeq 59.5$ nm/layer where a minimum transmittance value (or, equivalently, maximum averaged reflectance) is achieved. Despite s polarization presents better reflectance values than p states (due to the Brewster effect for p polarization [24]) the shape of both curves is similar. Subsequent numerical calculations with different layers' materials (not shown in this work) confirm that this average reflectance curve is of general nature. As the

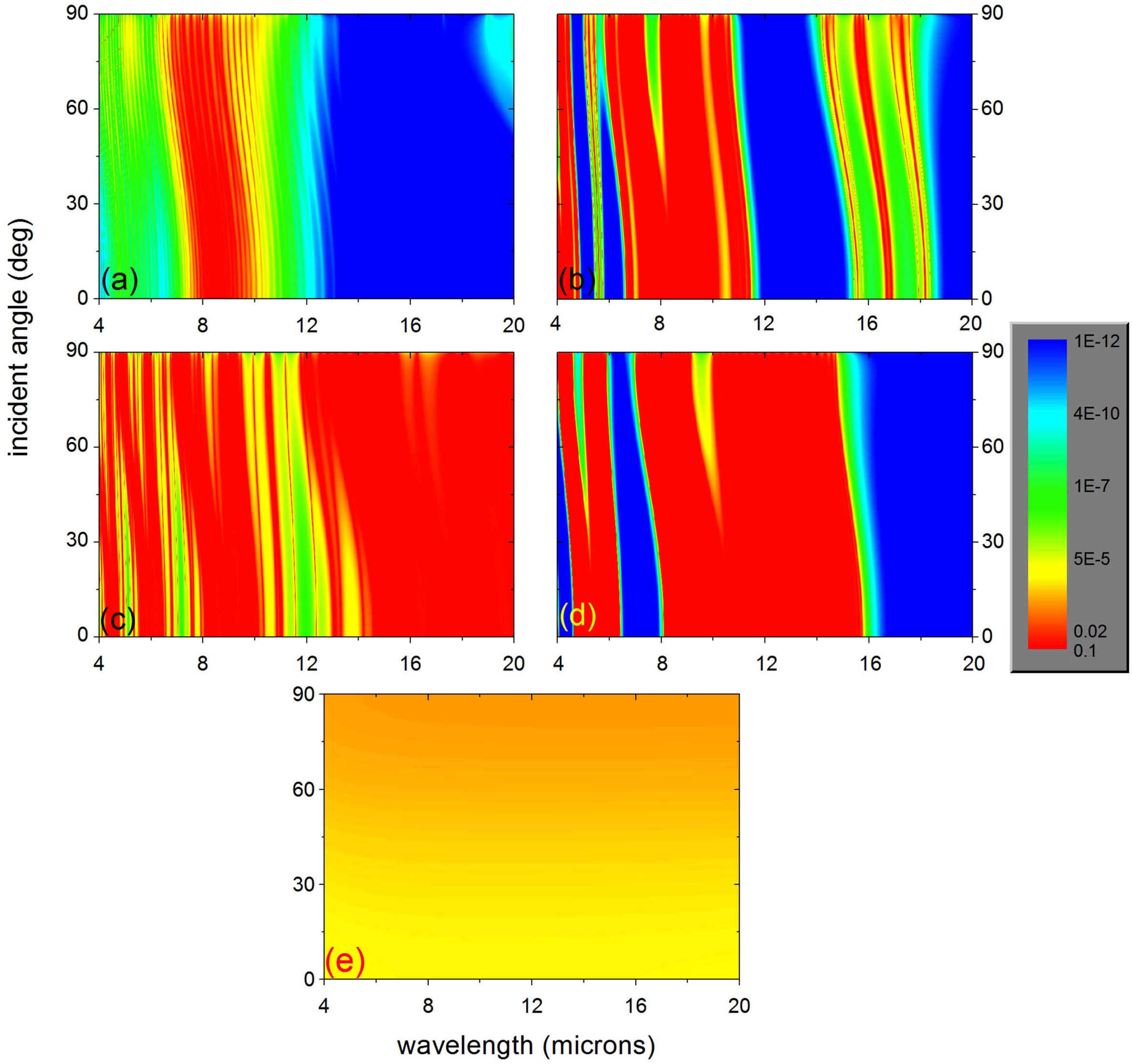

Figure 2. Transmittance values T versus the incident angle and wavelength for five different multilayer structures (and p-polarization) formed by the bilayer CsBr–Te. (a) Decreasing-width multilayer (48 layers, where $d_L^{(1)} = 3313.3$ nm and $d_H^{(2)} = 1037.7$ nm with a total length of 80 μm). The rate of thickness decrease for the CsBr layers corresponded to $a_L = -32.2$ nm/layer and the QW condition is fulfilled at 20 μm. (b) A QW Fibonacci distribution of 9th generation with 55 layers ($d_L = 2530.1$ nm and $d_H = 792.5$ nm). The total length of this QW Fibonacci multilayer was 80 μm. (c) A QW triadic Cantor structure of 3rd generation (27 layers, $d_L = 5400.0$ nm, $d_H = 1691.3$ nm and a total length of 75.5 μm). (d) A QW periodic multilayer (38 layers, $d_L = 3222.9$ nm, $d_H = 1009.4$ nm). The total length corresponded to 80 μm. (e) A disordered multilayer with a total random variation of the layers' thickness (48 layers with a total length of 80 μm and 500 disordered configurations for the averaging process).

aperiodicity of our DWM is increased, higher transmittance values are gained.

A reasonable explanation for the existence of such transmittance minimum is the following: when the decreasing rate a_L reaches the value -59.5 nm/layer, all of the layers in the structure satisfy the QW condition (which is a fundamental condition to improve the reflectance) over the entire 4–20 μm spectral range. It is easy to observe that the first layer (formed by CsBr and 3313.3 nm in length) fulfills the QW condition at a wavelength of 22 μm, whereas the last one (in this case Te and 162.7 nm) satisfies the same requisite at 3.5 μm. As the aperiodicity parameter $|a_L|$ is reduced, the shorter wavelengths do not present acceptable reflectance values. On the other hand, large decreasing rates $|a_L|$ lead to a loss of efficiency because thin (or ultrathin) layers do not contribute extensively to a reflectance improvement within this spectral range (in other words, we have less 'useful' layers in our DWM).

Once the optimization of our aperiodic structure has been carried out, let us now take a closer look at the transmittance values for the minimum average $\langle T \rangle$, that is, for $|a_L| \simeq 59.5$ nm/layer (see again figure 3, bottom panel). So, in figure 4 we display our numerical results for T, versus the incident angle and wavelength, for our best DWM (total length 59.5 μm). Remarkable reflectance values can be discerned (greater than $1 - 10^{-8}$) for practically the entire

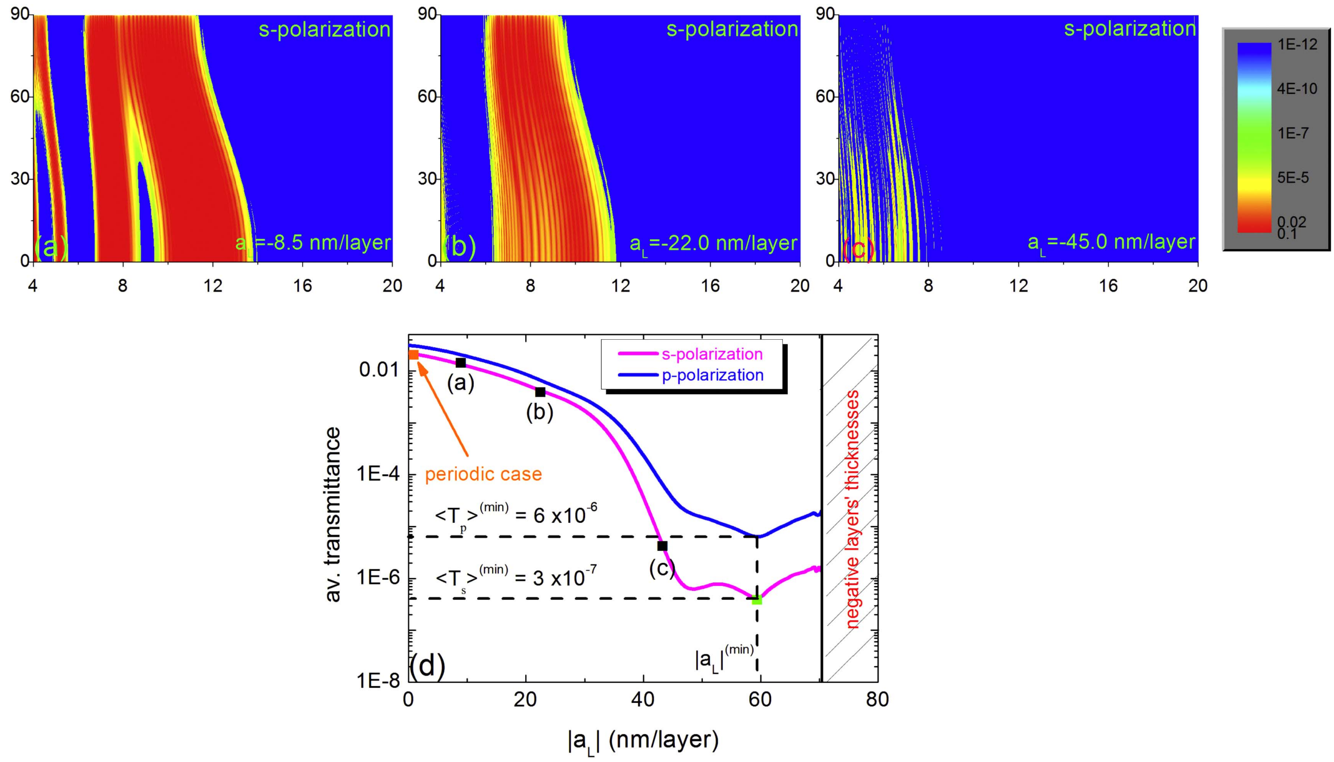

Figure 3. (Upper panels) Transmittance values of our decreasing-width multilayer versus the incident wavelength and angle (same number of layers and initial thickness as in figure 2(a)) for three different values of the thickness decrease rate a_L; (bottom panel) average transmittance $\langle T \rangle$ (over the entire spectrum and incident angles) as a function of the modulus of the parameter $|a_L|$. The three upper cases are also shown, labeled as (a), (b) and (c), respectively.

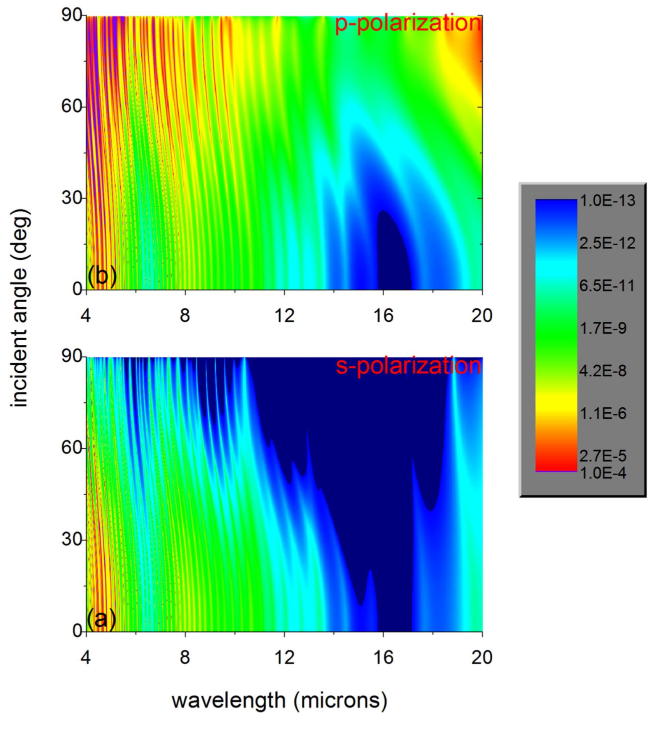

Figure 4. Transmittance values for our optimized DWM (48 layers with a total length of 59.5 μm) versus the incident angle and wavelength, where $d_L^{(1)} = 3313.3$ nm, $d_H^{(2)} = 1037.7$ nm and a thickness decrease rate of $|a_L| = 59.5$ nm/layer.

4–20 μm range, with a significant near-zero transmittance region (shown in deep blue) where $T \leqslant 10^{-12}$.

4. Conclusion

In conclusion, our CsBr–Te decreasing-width multilayer constitutes the first reported omnidirectional reflector achieving average reflectances of $1 - 6 \times 10^{-6}$ for p polarization and even better results ($1 - 3 \times 10^{-7}$) for s incident states in the 4–20 μm spectral range. Absorption losses are practically negligible, less than 0.25% for the total transmittance with respect to the ideal non-absorbing cases, so experimental devices (such as surface protection films against high-power irradiation or low-loss mirrors in laser cavities, among others) might benefit from our DWM reflector in the mid and far infrared.

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References

[1] Fink Y, Winn J N, Fan S, Chen C, Michen J, Joannopoulos J D and Thomas E L 1998 *Science* **282** 1679
[2] Chen K M, Sparks A W, Luan H-C, Lim D R, Wada K and Kimerling L C 1999 *Appl. Phys. Lett.* **75** 3805
[3] Lee H Y, Makino H, Yao T and Tanaka A 2002 *Appl. Phys. Lett.* **81** 4502
[4] Deopura M, Ullal C K, Temelkuran B and Fink Y 2001 *Opt. Lett.* **26** 1197
[5] Lin W, Wang G P and Zhang S 2005 *J. Mod. Opt.* **52** 1155
[6] Barriuso A G, Monzon J J, Yonte T, Felipe A and Sanchez-Soto L L 2013 *Opt. Express* **21** 30039
[7] Bouazzi Y, Soltani O, Romdhani M and Kanzari M 2014 *Prog. Electromagn. Res.* M **36** 1
[8] Kim S H and Hwangbo C K 2002 *Appl. Opt.* **41** 3187
[9] Xi J Q, Ojha M, Cho W, Plawsky J L, Gill W N, Gessmann T and Schubert E F 2005 *Opt. Lett.* **30** 1518
[10] Lee K H, Moon Y T, Song J O and Kwak J S 2015 *Sci. Rep.* **5** 9717
[11] Liu Z, Liu X, Wang Y and Pan P 2016 *J. Phys. D: Appl. Phys.* **49** 195101
[12] Moitra P, Slovick B A, Yu Z G, Krishnamurthy S and Valentine J 2014 *Appl. Phys. Lett.* **104** 171102
[13] Pleasants S 2014 *Nat. Photon.* **8** 498
[14] Slovick B, Yu Z G, Berding M and Krishnamurthy S 2013 *Phys. Rev.* B **88** 165116
[15] Berry M V and Klein S 1997 *Eur. J. Phys.* **18** 222
[16] Zhang D, Li Z, Hu W and Cheng B 1995 *Appl. Phys. Lett.* **67** 2431
[17] Li H, Chen H and Qiu X 2000 *Physica* B **279** 164
[18] del Barco O, Gasparian V and Gevorkian Z 2015 *Phys. Rev.* A **91** 063822
[19] del Barco O, Conejero E, Gasparian V and Bueno J M 2016 *Transport in Interacting Disordered Systems (Granada, Spain)* (http://um.es/bohr/files/moo/SlBarco.pdf)
[20] Bass M, Van Stryland E W, Williams D R and Wolfe W L 1995 *Handbook of Optics* vol 2 2nd edn (New York: McGraw-Hill)
[21] Palik E D 1995 *Handbook of Optical Constants of Solids* (New York/Amsterdam: Academic/Elsevier)
[22] Popescu M A 2000 *Non-Crystalline Chalcogenides* (Amsterdam: Springer) (https://doi.org/10.1007/0-306-47129-9)
[23] MacLeod H A 2010 *Thin-Film Optical Filters* (London: Taylor and Francis)
[24] Aronov A and Gasparian V 1990 *Solid State Commun.* **73** 61