High-reflectance composite metal coatings for planar-integrated free-space optics

Matthias Gruber, Thomas Seiler, and An-Chi Wei

For planar-integrated free-space optical (PIFSO) systems high-reflectance thin-film coatings are crucial. Evaporated metal films are preferred for their relative technological simplicity. We propose a three-layer Al−Ag−Al coating composition that combines the high reflectance of Ag with the chemical passivity of Al and its good adherence to glass. Two special measures are taken to prevent delamination: one is an anchoring of the edges of the coating in narrow ditches that are etched into the substrate and the other is the use of an adhesive Al underlayer; to reduce absorption this underlayer is implemented only in sparsely distributed discrete areas. The optical properties of such composite coatings are investigated theoretically. The fabrication complexity is only slightly increased compared to PIFSO systems with one-layer Al reflectors. In experimental tests we verified a reflectance of approximately 98% and an adherence comparable to that of simple Al coatings. © 2006 Optical Society of America

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1. Introduction

Planar-integrated free-space optics (PIFSO) is an integration approach that is based on miniaturizing and folding a free-space optical setup into a thick transparent wafer in such a way that its components are located at the plane wafer surfaces and optical signals propagate along zigzag paths inside the substrate.[1] Passive optical components such as lenses can be implemented through local modulation of the refractive index or, more commonly, through surface relief structuring. The 2D arrangement of all optical system components in PIFSO provides perfect compatibility with the design principles of very-large-scale integrated (VLSI) (opto) electronics and its established lithography-based fabrication methods; most important is the use of reactive ion etching (RIE) to realize multilevel surface-relief diffractive optical elements (DOEs). PIFSO has evolved into a heterogeneous integration platform for different kinds of microtechnologies (see Fig. 1) in recent years[2] with applications primarily (but not only) in optical information processing, optical sensors, and optical interconnects.[3–5]

The characteristic zigzag-type propagation of optical signals requires their confinement inside the planar substrate. One could make use of total internal reflection, but this would significantly complicate the optical system design by requiring a much more sophisticated nonparaxial treatment[6] and it would impose severe restrictions on the system geometries, in particular, on the achievable packaging density of optical components. Therefore, the use of reflective coatings is preferable. To be suitable for PIFSO, such coatings must satisfy the following conditions:

- Most important is a high reflectance because signal paths may easily involve a cascade of ten or more reflections.
- The deposition process has to be compatible with lithography to enable microstructuring of the reflective coating and thus a precise and arbitrary positioning of the reflecting areas on the wafer.
- The compatibility condition extends to all subsequent assembly steps of a PIFSO module. These steps may, for example, involve high-temperature processes such as flip–chip bonding of VLSI chips.
- Finally, of practical importance is a sufficient stability of the reflective coating with respect to environmental influences to prevent delamination, abrasion, and corrosion.

M. Gruber (Matthias.Gruber@FernUni-Hagen.de) and T. Seiler are with FernUniversität in Hagen, Juniorprofessur für Optische Mikrosysteme, Universitätsstrasse 27, 58084 Hagen, Germany. A.-C. Wei is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan.

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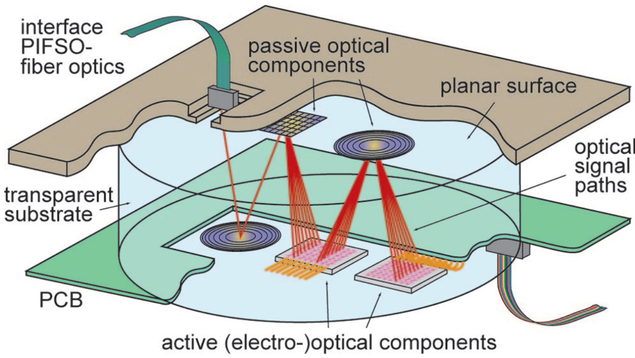

Fig. 1. (Color online) System concept of planar-integrated free-space optics. Optical signal paths are folded into a planar wafer that is transparent for the wavelength band of interest. Its thickness is of the order of millimeters. PCB, printed circuit board.

The central question that we investigate in this paper is how to satisfy these conditions at low cost and with the lowest possible technological effort [in addition to what is necessary to realize multilevel surface-relief DOEs (Ref. 7)]. That excludes reflective coatings based on dielectric stacks despite their superior performance potential because they are typically composed of many layers with precisely defined thicknesses, the fabrication of which requires a considerable technologial effort and usually high-end clean-room equipment. We focus instead on metallic coatings because their design is much more simple (ideally just one layer), their thickness is usually uncritical, and they can be used for a broad spectral region.

In Section 2 we recapitulate the basic optical and technological properties of metal thin-film coatings from the perspective of PIFSO. It turns out that none of the standard metal coatings satisfies all the above conditions, but evaporated Al and Ag films are good starting points to develop a problem-specific solution. Such a solution is presented in Section 3. It is a composite coating design that combines the high reflectivity of Ag with the chemical passivity and good adherence of Al. In Section 4 we estimate the optical performance of our proposed composite coating theoretically. Losses are due to absorption and (to a small degree) to diffraction. The PIFSO-relevant properties of the composite coating approach were also determined in practical tests, which is the topic of Section 5. In Section 6 further design options are briefly outlined.

2. Important Properties of Metal Coatings

The use of metals for reflectors has a long history, beginning with the simplest form of a polished surface of the bulk material, and evolving into the modern form of thin films on carrier substrates. If the carrier substrate is transparent, two basic types of operation are possible that are commonly referred to as front-side and back-side mirrors (Fig. 2). The design criteria for the latter mirror type are relevant for PIFSO where optical signals also impinge from the carrier side onto the carrier–metal interface. Assuming an idealized flat boundary the reflectance R can be calculated by the Fresnel formulas using complex refractive indices $n - ik$.[8] Assuming, furthermore, orthogonal incidence (which is usually a permissible approximation for PIFSO systems), an insulating substrate material (which implies $k_0 = 0$), and a sufficiently thick metal layer ($\gg$skin depth), the following (polarization-independent) term is obtained:

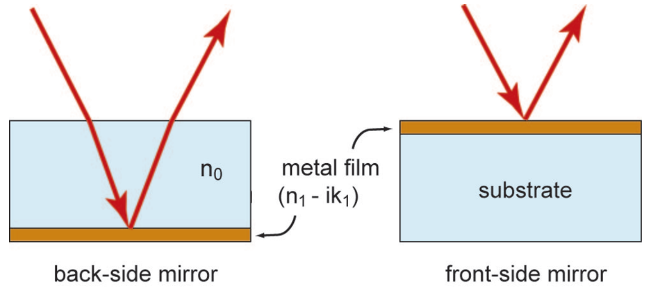

Fig. 2. (Color online) Front-side and back-side operation of a thin film reflector.

$$R = \frac{(n_0 - n_1)^2 + {k_1}^2}{(n_0 + n_1)^2 + {k_1}^2}. \tag{1}$$

A typical feature of metal–dielectric interfaces is that the reflection is accompanied by a phase shift φ that is, in general, different from 0 or π, as in the case of dielectric–dielectric interfaces. This is due to the finite extinction coefficient k_1 and quantitatively expressed by

$$\tan \varphi = \frac{2n_0 k_1}{{n_0}^2 - {n_1}^2 - {k_1}^2}. \tag{2}$$

Since the refractive index and absorption coefficient are functions of wavelength λ, the same holds true for the reflectance and the phase shift. Table 1, which is based on the material data provided by Ref. 9, lists the R and φ values of various metal coatings on fused silica (the most frequently used PIFSO wafer material so far) for $\lambda = 850$ nm; this wavelength is chosen here because of its particular importance for short-range optical communication and related PIFSO applications. Included in Table 1 are the values for the respective metal–air interfaces to underline that the back-side operation of a metal reflector tends to lower its optical performance; that effect is particularly strong for Al.

For a practically useful characterization of metal coatings, several other properties in addition to the (bulk material) reflectance are crucial,[10] among them adherence to the carrier substrate, chemical stability, and the lattice–material structure of the deposited film. These properties are largely determined by the materials (a rating of the metals Al, Ag, Au, Cu, and Ti on fused silica is given in the lower part of Table 1), but the deposition technique also plays a role. For PIFSO physical techniques appear most suitable, es-

Table 1. Various Performance Parameters of Metal Thin Films on Fused Silica for λ = 850 nm

Property		Al	Ag	Au	Cu	Ti
Metal–SiO_2	R^a	0.8099	0.9841	0.9829	0.9506	0.5068
	φ^a	21.34	27.96	32.61	30.90	25.72
Metal–Air	R	0.8627	0.9887	0.9877	0.9645	0.6202
	φ	14.71	19.39	22.70	21.47	17.53
Adherence[b]		+	−	−	0	+
Chemical stability[b]		+	−	+	0	+

[a]The values for R and φ (in degrees) are calculated with Eqs. (1) and (2) using the bulk material parameters from Ref. 10 and $n = 1.453$ and $n = 1$ for SiO_2 and air, respectively.
[b]The plus, zero, or minus ratings for adherence and chemical stability are based on Refs. 8 and 9.

pecially evaporation and sputtering. Sputtering will normally outperform evaporation in terms of adherence; however, it is technologically much more complex[8] and therefore will not be considered further.

Traditionally, reflective coatings for PIFSO have been made by high-vacuum evaporation of Al. The material is easy to handle, its adherence to fused silica is excellent, and Al films are stabilized by the natural oxide layer on the surface (see Table 1). The problem is the reflectance, especially for the important wavelength of 850 nm. Even under optimal processing conditions[11] R can barely exceed the 80% mark, which is not sufficient to produce energetically efficient PIFSO systems. Of particular interest as a substitute coating metal is Ag because it has the highest reflectance of all metals for $\lambda = 850$ nm and $R > 0.95$ throughout the whole visible and near infrared wavelength region. This broadband feature is the main reason to favor Ag over Au as it makes a reflective coating suitable for a larger variety of applications. The problems with Ag are its insufficient chemical inertness (especially in building compounds with sulfur) and its poor adherence to glass. The first shortcoming can be neutralized with suitable protective overcoatings (albeit at the expense of increased fabrication complexity) but the second one is a more severe obstacle.

One suggestion to overcome this poor adherence to glass is the use of an underlayer (between the substrate and the Ag film) that provides adhesion.[12] A suitable material for such an underlayer would be Ti or Al. However, for back-side operation it needs to be thin enough that the optical properties of the reflector are still dominated by the Ag layer behind it. The thickness of the underlayer should therefore not exceed the equivalent of a few atomic layers, which is difficult to control with low-end thermal evaporation equipment. Therefore, we consider an alternative solution, which is presented in the following section and that is based on spatially structured Ag–Al compound coatings.

3. Spatially Structured Compound Coatings

Our approach to the construction of reflectors that are both highly reflective and adherent to a PIFSO wafer is also based on Ag with an underlayer, but the underlayer is not continuous. Instead it is reduced to sparsely and randomly distributed tiny patches that cover only a small fraction of an optical component (see Fig. 3) and serve as discrete "bonding pads" to prevent delamination of the Ag layer. For most of its area, the Ag layer is in direct contact with the PIFSO wafer; the reflectance of the entire coating is therefore almost exclusively determined by Ag, and the thickness of the underlayer becomes irrelevant. Our approach can be seen analogous to the laser photocoagulation method that is used in ophthalmology to prevent retinal detachment. To shield the Ag layer from the environment, an overcoating is deposited on top. We find that Al is a suitable material for both the structured underlayer and the overcoating due to its desirable adherence properties, its chemical passiv-

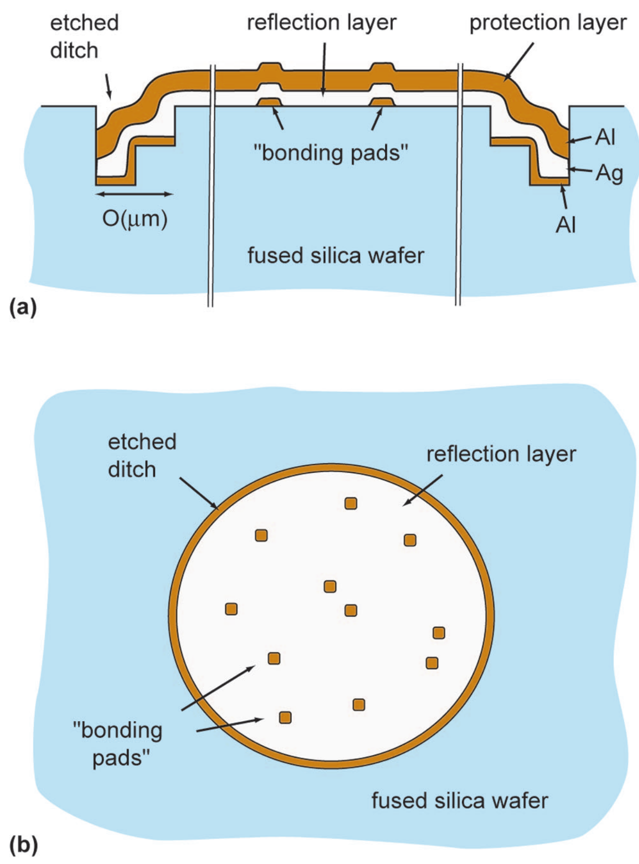

Fig. 3. (Color online) (a) Cross-section and (b) bottom-side view of the proposed Ag–Al compound thin-film reflectors for PIFSO.

ity, and that the corrosion process of Ag is chemically inhibited in the presence of Al.[13]

The fabrication of such a composite reflector requires two lithographic working steps (one more than conventional PIFSO reflectors), each consisting of the three processes: lithographic copying into photoresist; evaporation of metal(s), and lift-off. In the first working step, the Al bonding pads are realized; in the second, the Ag layer and the protective Al overlayer follow. The final two layers can be deposited with one lithographic step (by sequential evaporation of Ag and Al) because they have the same spatial distribution.

In addition to improving the adherence across the area of a PIFSO reflector, we are particularly concerned with stabilizing its edges where a destructive peeling process usually starts. The stabilization is achieved by anchoring the edges in etched ditches that surround the reflector sections as shown schematically in Fig. 3. The ditches are narrow (typically of the order of a micrometer) and deeper than the total thickness of the composite coating, which is typically between 100 and 300 nm. This ensures a good bracing and enables direct contact between the top Al layer and the PIFSO substrate at the outer flank of the ditch, which means that the sensitive Ag layer is hermetically sealed by the protective Al overlayer. It should be noted that the Al at the bottom of the ditches is deposited in the first working step, i.e., as a part of the structured underlayer. The etching of the ditches does not increase the fabrication effort for a PIFSO system because it can be carried out together with the fabrication of the multilevel DOEs.

With our composite design approach, evaporated reflectors should comply with the nonoptical criteria that were defined in Section 1. In Section 4 we will further examine their optical performance.

4. Optical Performance Estimation

The reflectance of a composite coating according to Fig. 3 can be estimated rather simply by the weighted average of the reflectances of Al and Ag in the form

$$R = R_{\mathrm{Al}}\frac{A_{\mathrm{Al}}}{A_{\mathrm{tot}}} + R_{\mathrm{Ag}}\frac{A_{\mathrm{Ag}}}{A_{\mathrm{tot}}}, \qquad (3)$$

where $A_{\mathrm{Al}}/A_{\mathrm{tot}}$ and $A_{\mathrm{Ag}}/A_{\mathrm{tot}}$ express the relative areas that the two metals effectively cover. By keeping the Al fraction small we can obtain an overall R value close to that of Ag. For example, if the bonding pads cover no more than 2% of the total reflector area, the reflectance remains above 98%; more detailed information is listed in Table 2.

A second issue that needs to be investigated is how sacrificing the spatial invariance of the coating composition affects the optical performance. In effect, a reflective coating similar to Fig. 3 needs to be interpreted as a DOE that (even without any surface relief) spatially modulates both the amplitude and the phase of an incoming beam. The first type of modulation is due to the local variation of the reflectance, and the second one to the locally different phase shifts of Ag and Al, according to Table 1. If this property leads to a substantial diffraction of light into unwanted orders, the effect is tantamount to a reduced effective reflectance of the coating.

Table 2. Optical Performance Parameters for Different Composite Ag–Al Reflector Compositions on Fused Silica for $\lambda = 850$ nm

$A_{\mathrm{Al}}/A_{\mathrm{tot}}$	0.01	0.02	0.04
R [by Eq. (1)]	0.9823	0.9805	0.9771
η (diffraction)	0.9998	0.9996	0.9992
R (effective)	0.9821	0.9801	0.9763
SNR (average)	79.3 dB	76.2 dB	73.6 dB
SNR (worst case)	67.8 dB	63.8 dB	60.6 dB

To quantify this type of efficiency loss, computer simulations were carried out in which the composite coating was modeled as a pixelated two-dimensional DOE. Assuming uniform plane-wave illumination, the reflected light field is represented by a matrix, the elements of which either take on a value $U_{\mathrm{Ag}} \propto \sqrt{R_{\mathrm{Ag}}}\exp(i\varphi_{\mathrm{Ag}})$ or $U_{\mathrm{Al}} \propto \sqrt{R_{\mathrm{Al}}}\exp(i\varphi_{\mathrm{Al}})$ with R_{Ag}, φ_{Ag}, R_{Al} and φ_{Al} being the values of Table 1. We are interested in the Fraunhofer diffraction pattern of such a light distrubution that can be obtained by a numerical Fourier transformation $U(x, y) \xrightarrow{\mathrm{FFT}} \tilde{U}(\mu, \nu)$.

The diffraction loss is given by the accumulated intensity of all nonzero orders. We find that for the given parameters (Tables 1 and 2) this loss is not higher than an order of 10^{-4} relative to the total intensity of the incoming beam. This means it is negligible in practice. Furthermore, the diffracted light is rather uniformly distributed over all nonzero orders as can be seen from the plots of a typical power spectrum in Fig. 4. Defining as the signal-to-noise ratio (SNR) the intensity ratio between the zeroth and a nonzero diffraction order, we find that it is typically of the order of 70 dB (Table 2). This high value is due to the random distribution of the bonding pads across the area of an optical component. With a more regular patch distribution the power distribution across the diffraction pattern would be less uniform and the SNR would be worse.

From this evaluation we conclude that our approach with spatially structured composite Ag–Al reflectors is recommendable in terms of achievable reflectance and permissible in terms of diffraction losses.

5. Experimental Tests

To confirm our theoretical expectations in practice we fabricated several composite Ag–Al reflector samples and tested them experimentally. An intermediate fabrication step is documented in Fig. 5, which shows parts of two optical components. The left one (a diffractive lens) contains an etched multilevel surface profile the edges of which can be clearly seen, and the right one is a plane mirror; both components are surrounded by the etched anchoring ditches. In Fig. 5, the first Al deposition step has been completed,

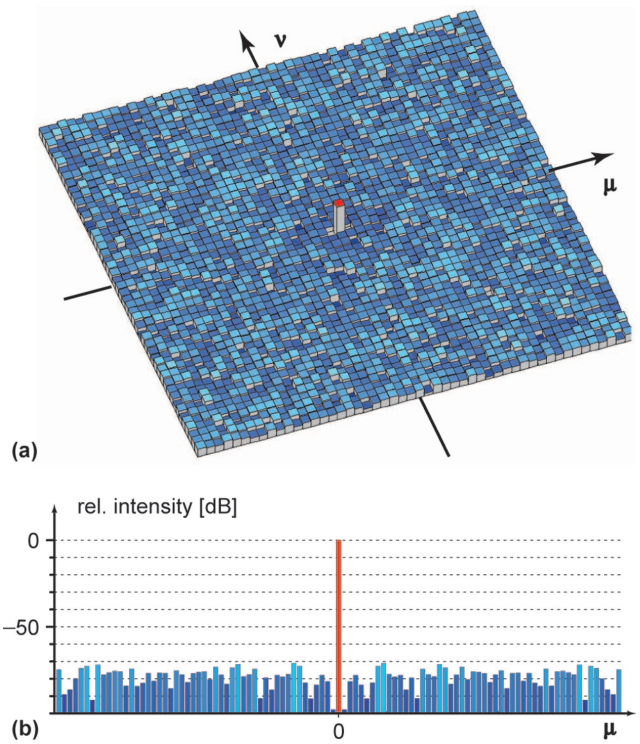

Fig. 4. (Color online) (a) Color-coded pseudo-three-dimensional plot of a typical computed diffraction pattern generated by a Ag–Al compound-type reflector; (b) logarithmic intensity scan along the μ axis.

which generates the bonding pads (covering 1% of the total area in this example) and the Al underlayer in the ditches.

In the (fully finished) specimen shown in Fig. 6, the composite reflector (again with $A_{Al}/A_{tot} = 1\%$ and $A_{Ag}/A_{tot} = 99\%$) was overcoated with an Al layer of

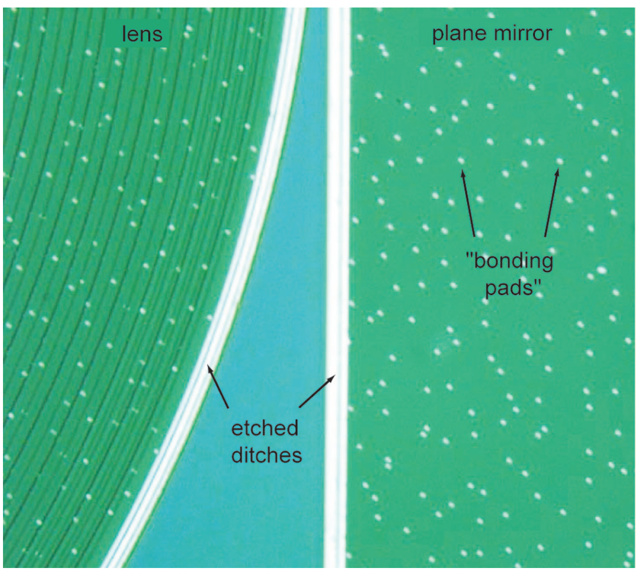

Fig. 5. (Color online) First fabrication step for the proposed compound-type reflectors: realization of the Al bonding pads and the underlayer in the anchoring ditches.

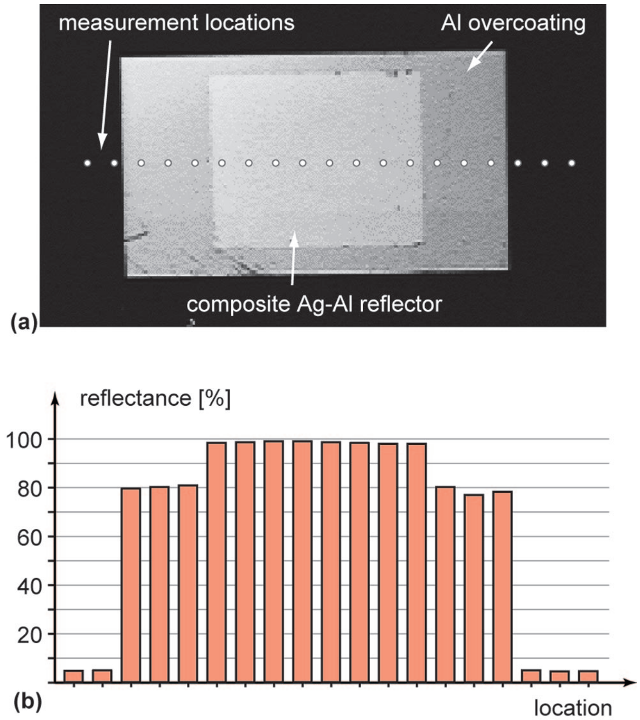

Fig. 6. (Color online) Picture of an experimental specimen. The difference in reflectance between Ag and Al was evaluated by measurement and is also obvious visually.

larger size to enable a relative measurement of the optical properties of the proposed new coating type and the conventional coating type. The higher reflectance of the composite coating is already obvious from a visual inspection.

To evaluate R quantitatively, we used a setup in which the beam from a stabilized laser ($\lambda = 850$ nm) was reflected from the mirror being tested and focused onto the detector of a powermeter. For calibration of the measured intensity values, a commercial dielectric mirror was used and it was assumed that its reflectance is 99.9% as specified. In this way we obtained $R = 0.807$ for Al and $R = 0.980$ for the composite coating, which is in good agreement with the theory (Table 2). The calibration and measurement cycle was repeated several times to check the repeatability of our results. It was found that the R values were stable down to the second decimal digit.

The same measurements were repeated after the specimen had been stored in an office desk for almost two years; this time we obtained 0.806 and 0.978, which leads us to the (tentative) conclusion that the protective Al overlayer does fulfill its function (at least if the environmental conditions are not very harsh, as in our case). In another test we implemented composite coatings with different percentages A_{Al}/A_{tot}. The total area that the Al patches cover was thereby adjusted by their number while their individual size of 2 μm × 2 μm was kept constant. It was confirmed experimentally that the reflectance then follows Eq. (3) and that diffraction losses are negligible (Table 2).

As for the mechanical properties (in particular adherence to fused silica), we found that composite coatings clearly outperform pure Ag coatings. For example, they withstand ultrasonic cleaning of a PIFSO module without damage, whereas our Ag coatings would delaminate completely in this process. Ultrasonic exposure also proved that the tiny Al patches are necessary because simplified composite coatings without them would sometimes delaminate, especially when the reflector area was large. With the currently used lithography and deposition processes the composite coatings do not pass a Scotch tape test—they will be pulled off with the tape. However, since the same happens to our conventional Al coatings and since it is well known that commercial Al coatings can pass the Scotch tape test, it is reasonable to conjecture that the fabrication process of composite Ag–Al coatings can be refined such that these coatings also pass a Scotch tape test.

6. Conclusion

We have proposed an approach for realizing thin-film reflective coatings that match the particular requirements of PIFSO. It is based on a three-layer Ag–Al compound structure and combines the superior optical properties of Ag with the good adherence and the chemical passivity of Al. The fabrication requires two lithography and evaporation steps. In the first step, an underlayer of sparsely and randomly distributed Al patches is deposited. In the second step, the actual Ag reflector layer and a protective Al overlayer follow. The expected optical and mechanical benefits of our approach were verified experimentally.

If a PIFSO module with such composite coatings is to be used outside of the laboratory it should be equipped with an additional overlayer that protects the optical components from scratching and absorbs stray light. An epoxy-based black lacquer is an ideal material for this purpose, as it is often used for commercial optical instruments.

To improve the adherence of the coating to fused silica such that it passes a Scotch tape test, one could adopt a method that has been described in the literature,[8,10] namely, a cleaning of the substrate surface just prior to the evaporation process by a glow discharge. This will remove surface oxides and adsorbed gas molecules that are responsible for the weaker bonding forces between metal and substrate. On the other hand, it also means that the technological effort is increased.

Another issue that might be further investigated is a matching of the spatial distribution of the bonding pads in the underlayer and the function of the respective optical component. For example, if the component is a diffractive Fresnel lens one could define a fraction of all rings (those that correspond to a certain phase delay) as an area for the Al patches and adapt the etch depth such that, together with the phase shifts due to Eq. (2), the respective required phase delay is realized.

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