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INDUSTRIAL AND ENGINEERING PAPER

Low-cost dichroic mirrors for future Deep Space ground stations

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Future Deep Space (DS) ground stations envisioned by running projects funded by major space agencies are based on arrays of reflector antennas operating in different frequency bands. Therefore, a multi-band feeding system is required for each antenna, and a possible solution foresees the use of dichroic mirrors to separate/combine different beams. This paper presents a low-cost and fast manufacturing process for the fabrication of dichroic mirrors, usually referred to as punching technique or metal stamping. In particular, the specific advantages and limits of this fabrication technique are outlined and discussed, showing both electrical performance and manufacturing accuracy measurements from a test prototype. In addition, a typical scenario for future DS ground stations is described, showing the impact of these low-cost dichroic mirrors on the final ground station performance and cost, compared to the standard approach for dichroic mirror manufacturing based on more expensive and time-consuming technologies (e.g. milling machining).

Keywords: dichroic mirrors, ground station, low-cost manufacturing, metal stamping

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I. INTRODUCTION

In the next years, all major space agencies intend to enhance the performance of their Deep Space (DS) ground stations to support future missions with high bit-rate to download high-definition images and scientific data. At present, the state-of-the-art DS ground stations are based on a single large reflector antenna with the main dish diameter of the order of 35 m [1, 2]. According to future specifications posed by the European Space Agency, the area of the ground station should be enlarged to a factor between 4 and 10 (i.e. 6–10 dB) [3].

A possible solution to increase the collecting area consists in using even larger reflectors, with diameter up to 70 m (6-dB scenario) or to 110 m (10-dB scenario) [2, 4]. However, this option turns out to be very expensive and exhibits little flexibility. In fact, the main reflector of such large antennas can be strongly deformed by gravity, thermal, and wind loads, which can be only partially recovered by complex systems based on active panels. In addition, a single large antenna represents a critical single-point failure architecture, posing significant risk to the availability of the ground segment.

A more promising solution is based on arrays of smaller reflector antennas that exhibit a total large collecting area. The optimum ratio between the required number of antennas and the antenna diameter is still debatable, but examples of arrays using a large number of small-to-medium-sized antennas have been already implemented for radio-astronomy applications, based on tens or hundreds of antennas with a diameter of around 6 m [5]. In this case, an enhancement of the collecting area of 6 dB would require 136 6-m antennas whereas an enhancement of 10 dB would require 344 6-m antennas.

In this scenario, a serious bottleneck of the system is the feeding network of each antenna, which is usually operated at different frequency bands. Although the development of multi-band feeds (Fig. 1(a)) is often complicated and expensive [2, 5], the solution based on dichroic mirrors appears as a viable alternative: one or more dichroic mirrors can be adopted as quasi-optical filters to combine/separate signals at different frequencies, generated by simple and relatively cheap standard corrugated horns (Fig. 1(b)). However, being the number of antennas to be deployed very large, this type of solution leads to an economical benefit over multi-band feeds only if low-cost dichroic mirrors can be developed.

Dichroic mirrors for deep-space antennas usually consist of metallic plates perforated periodically by apertures with arbitrary shape [6]. Several manufacturing technologies have been adopted to fabricate all-metal dichroic mirrors, including milling technique, electrical discharge machining, and water-jet cutting [2, 7]. The milling technique permits one to realize the apertures by drilling an arbitrarily shaped hole with a rotating tool. This technique is widely adopted due to its accuracy and availability of machines able to handle large metallic plates, but it is rather slow and expensive. Electrical discharge machining is based on an electric discharge along a metal wire that defines the aperture shape. Due to the very small diameter of the wire, this technique permits one to realize apertures with sharp corners, but it is very expensive. In water-jet cutting, the apertures are created by means of a high-pressure water beam added with fine sand grains. This technique is cost effective, but it determines conical-shaped apertures due to the natural divergence of the water beam.

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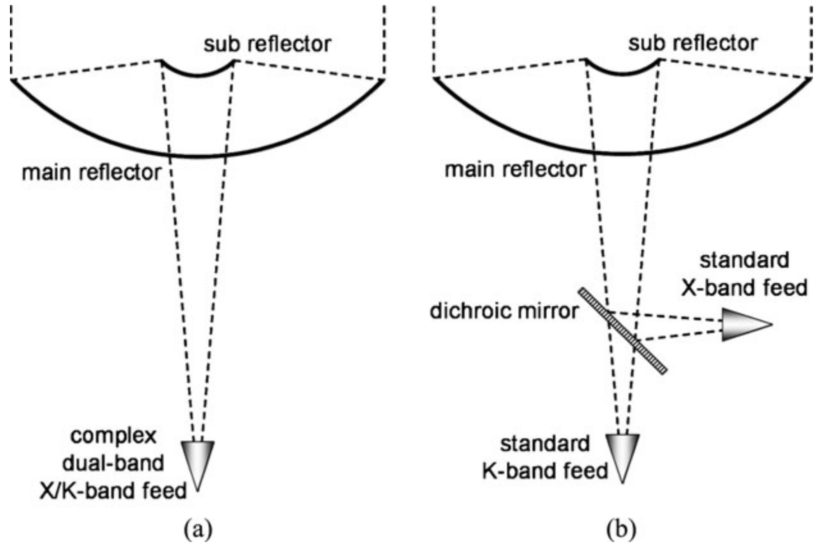

Fig. 1. Schematic of the layout of an antenna working in X and K bands: (a) with single multi-band feed and (b) with two single-band feeds and a dichroic mirror (drawing not to scale).

In this paper, a different manufacturing technique, conventionally named punching or metal stamping, is investigated through the design, fabrication, mechanical testing, and electrical measurement of a test prototype. The fabrication accuracy, the electrical performance, and cost effectiveness are discussed for the scenario envisioned for future DS ground stations.

II. TEST PROTOTYPE DESIGN

As a case study, in this work we consider the future 6-m antennas operating in X band (7.145 ÷ 7.235 and 8.4 ÷ 8.5 GHz) and K band (25.5–27 GHz) for circular polarization. While the X band is used since many years for DS application and it is considered mandatory for this type of antennas, the K band is relatively new for DS communications: in fact, K band has been restricted for many years primary to Near Earth applications and only recently it has been allocated also for DS missions (ITU World Radiocommunications Conference in 2003 (WRC-03), entering formally into force in 2005), where its broad operation bandwidth (1.5 GHz) is considered particularly useful for the downlink of high-resolution images and to get high data rates.

Therefore, the dichroic mirror to be developed and manufactured by means of the punching technique is intended to reflect the X band and to transmit the K band (Fig. 1(b)). The punching technique permits one to realize the apertures of the dichroic mirror by pressing the metal plate between two appropriate custom-shaped metal tools, as shown in Fig. 2. It is extremely fast and cheap and it is commonly used to realize a wide range of general-purpose industrial grids, with a maximum plate dimension exceeding 1 m. The most critical limitations of the punching technique lie on the maximum thickness of the metal plate, which is limited to a few millimeters, and on the separation between adjacent apertures, also limited to a minimum value to avoid permanent deformations of the metal plate. In particular, in the first approach to study the applicability of the punching technique to microwave devices, both the thickness t and the minimum separation s between adjacent apertures are set to 2 mm (Fig. 3(a)), even if this choice does not represent the ultimate technological limit for punching. This means that

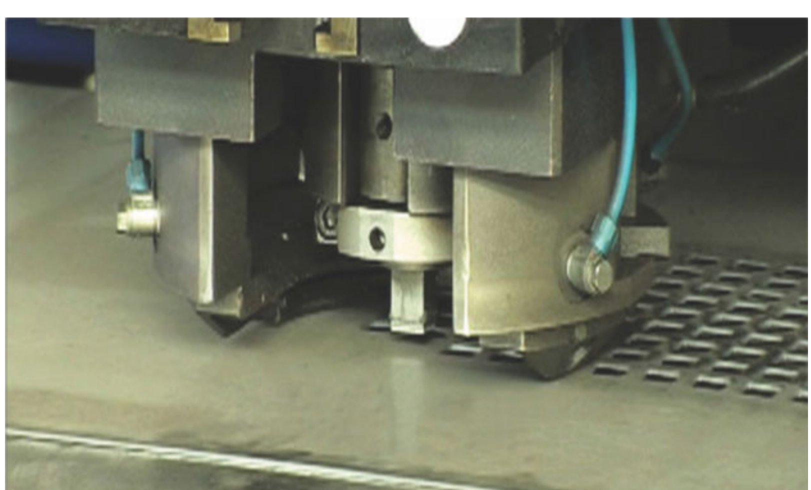

Fig. 2. Example of numerical controlled machine used for punching.

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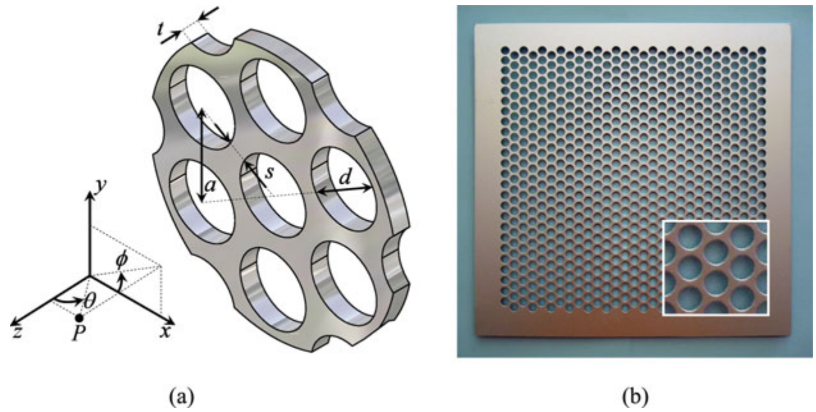

Fig. 3. Prototype of the dichroic mirror: (a) schematic of the unit cell with reference system and (b) photograph.

the performance expected from these dichroic mirrors is not directly comparable with the behavior exhibited by mirrors fabricated by other, more costly manufacturing processes that are not constrained to such limits (e.g. an X/K band dichroic mirror designed to be fabricated with milling is reported in [8]).

However, while state-of-the-art mirrors fabricated by means of costly techniques are usually intended as single pieces for a specific high-performance antenna (thus the cost is not usually a critical parameter), in the considered scenario the deployment of many antennas imposes a careful evaluation of the reproduction cost of the single units, including dichroic mirrors.

The aperture shape for the test prototype discussed in this paper is chosen to be circular. In fact, even if the punching technique is perfectly suitable to fabricate a vast set of possible apertures (e.g. crosses, rectangles), a circular shape, being defined by only one parameter (i.e. the diameter d), allows for effectively and efficiently investigating how this parameter is affected by the punching technique. More complex shapes would jeopardize the possibility to clearly understand the relationship between the manufacturing process and the final unit. Therefore, while all these constraints (i.e. maximum thickness t, minimum separation s, aperture shape) could be relaxed with some benefits in the electrical performance of the dichroic mirror, the main objective of this work was to investigate the flexibility of this manufacturing technique rather than an optimum design.

Given the constraints discussed above, the diameter d of the circular aperture and the nominal incidence angle (θ_o, ϕ_o defined according to the canonical spherical coordinate system shown in Fig. 3(a)) have been optimized by using a well-proven in-house-developed software, based on the MoM/BI-RME method [9]. In particular, the design phase aimed to obtain a good transmission in K band while maintaining a good reflection in X band, as dictated by the scenario previously discussed. The final values are $d = 8$ mm for the diameter and $\theta_o = 15^\circ$, $\phi_o = 0^\circ$ for the incidence angle. Moreover, a triangular lattice has been chosen to mitigate as much as possible the effects of grating lobes. The separation between adjacent apertures $a = 10$ mm directly follows from the fixed parameter $s = 2$ mm and the optimized variable $d = 8$ mm.

The simulated reflection and transmission coefficients for both transversal electric (TE) and transversal magnetic (TM) modes are reported in Fig. 4, together with the cross-polarization for circular polarization, calculated according to [10].

Around 26 GHz the dichroic mirror exhibits a pass-band behavior. However, at around 27.5 GHz a stop-band peak is also exhibited for the TM mode due to the presence of the cut-off of higher-order modes. Although the proximity between the pass-band and the stop-band limits the performance of this dichroic mirror, it is remarked that this is due to the layout of the test prototype that was in turn dictated by the mechanical constraints discussed above. In fact, these constraints were aimed to assess the manufacturing process rather than to the best possible layout. In X band, i.e. around 7–8 GHz, the dichroic mirror exhibits an almost total reflection for both linear modes with very low cross-polarization.

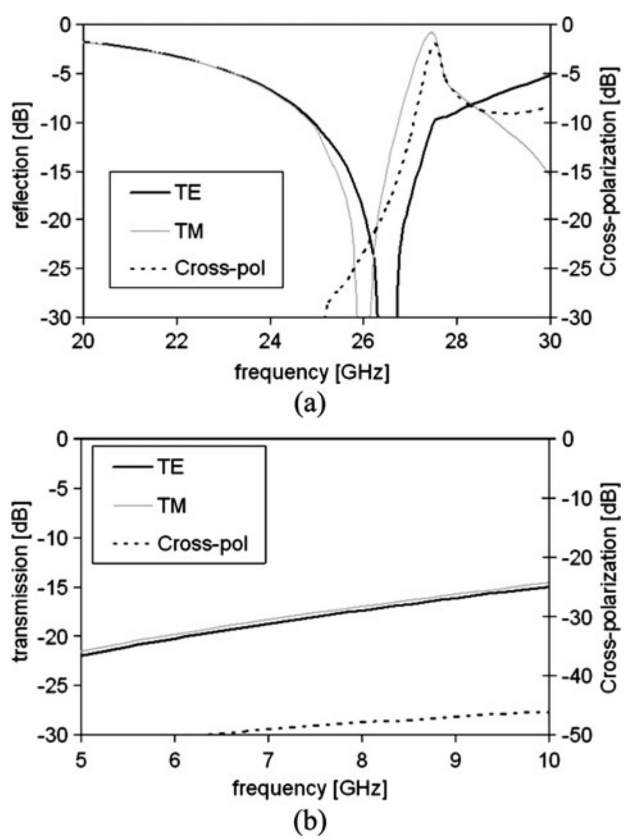

Fig. 4. Simulated performance of the test prototype: (a) reflection for TE and TM modes and cross-polarization for transmitted circular polarization and (b) transmission for TE and TM modes and cross-polarization for reflected circular polarization.

In order to evaluate the impact of the dichroic mirror on the array, especially for the transmitted band, a 6-m reflector antenna of the type schematically depicted in Fig. 1(b) has been simulated at 26.25 GHz with and without (i.e. with a perfect transparent mirror) the dichroic mirror, using a well-known commercial software based on physical optics [11]. In both cases the adopted horn illuminates the sub-reflector of the antenna with a Gaussian-like radiation pattern.

The results are shown in Fig. 5 and they are presented for a radiation cut along $\phi = 45^\circ$, being this cut the worst case in terms of cross-polarization. Compared to the case without dichroic mirror, the overall antenna maximum gain is reduced by 0.23 dB (Fig. 5(b)). The cross-polarization within the 1-dB contour of the co-polarization peak is more than 30 dB, less than the co-polarization peak. The first side lobe remains around 20 dB less than the co-polarization peak. The radiation pattern with the dichroic mirror also exhibits a small squint. This effect is well known for this type of antennas and it is only due to the finite thickness of the dichroic mirror, regardless of the manufacturing approach adopted, which generates a shift of the beam radiated by the horn (Fig. 5(b)). However, this misalignment is fully recoverable by proper lateral horn displacement, a classical technique usually adopted to compensate this effect, not discussed here due to space constraints.

III. TEST PROTOTYPE MEASUREMENT

Five identical test prototypes of the dichroic mirror have been manufactured out of a standard aluminum plate with dimension 30 × 30 cm^2, by punching around 400 apertures for each dichroic mirror (Fig. 3(b)).

First, the mechanical accuracy of the prototypes has been measured by a numerical control machine that can automatically verify the relevant geometrical dimensions. The results of this measurement campaign, reported in Fig. 6, show a mean value for the aperture diameter of 7.978 mm (22 μm less than the nominal design) with a Gaussian-like distribution with variance of around 10 μm. Similarly, the mean value for the aperture separation resulted in 10.005 mm (5 μm more than the nominal design) with a Gaussian-like distribution and variance of around 8 μm. These values can be considered fully comparable with the standard accuracy provided by more costly fabrication techniques, such as the milling. Therefore, one of the most critical point for the applicability of the punching technique to microwave devices is demonstrated.

The electrical performance of a prototype has been measured both in X and in K bands to verify the simulation data. The measurement setup consists of two horn antennas aligned with respect to the dichroic mirror to obtain an incidence angle of 15°. This setup allows for measuring the magnitude of the reflection coefficient for the K band and the magnitude of the transmission coefficient for the X band. In addition, absorbing material was adopted to mitigate the effects of external interferences. The measured and simulated reflection and transmission coefficients are reported in Fig. 7, along with the simulated tolerance bands calculated from 1000 simulations based on the statistical distribution reported in Fig. 6.

In K band, for both TE and TM polarization, the agreement between simulations and measurements can be considered

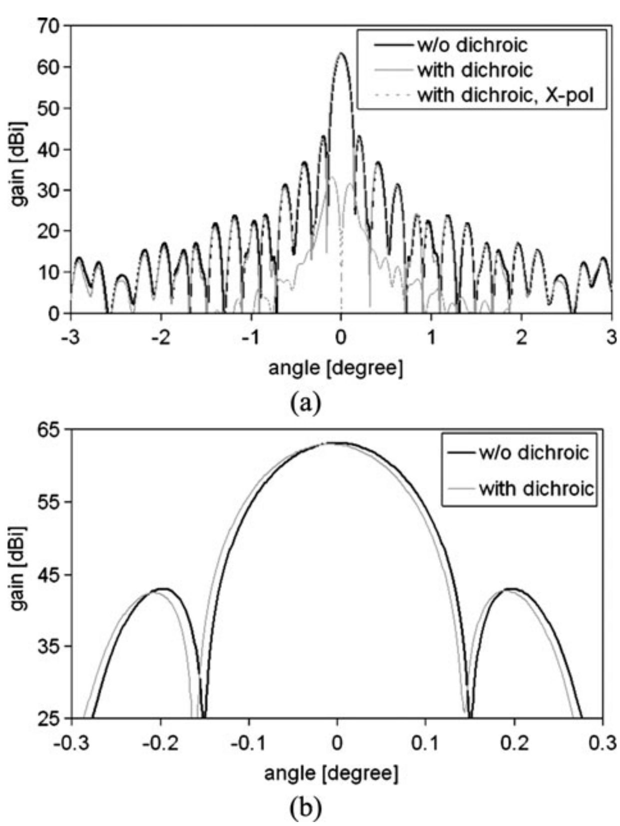

Fig. 5. Simulated 6-m antenna radiation patterns at 26.25 GHz for $\phi = 45^\circ$: (a) large-angle view with cross-polarization and (b) narrow-angle view.

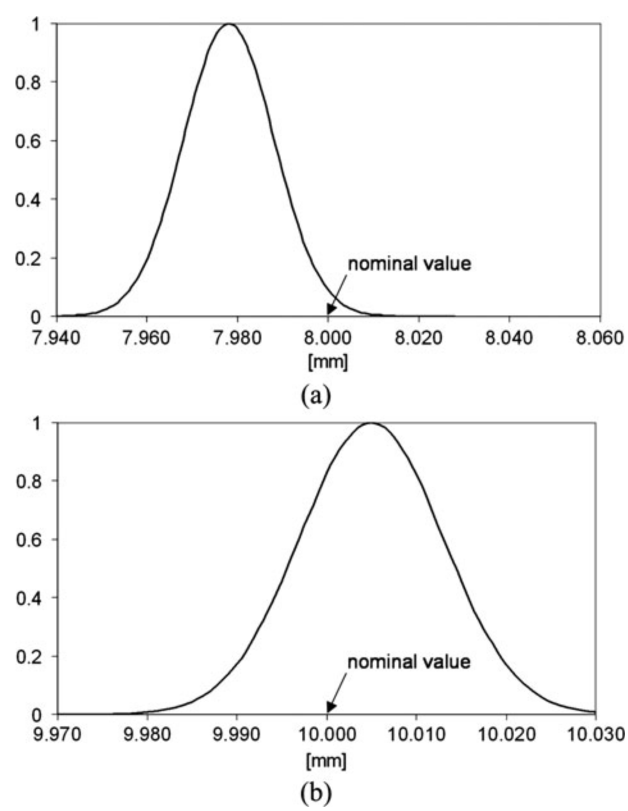

Fig. 6. Statistical distribution of the fabrication accuracy for the test prototype: (a) diameter of the aperture, nominal value 8 mm and (b) separation among apertures, nominal value 10 mm.

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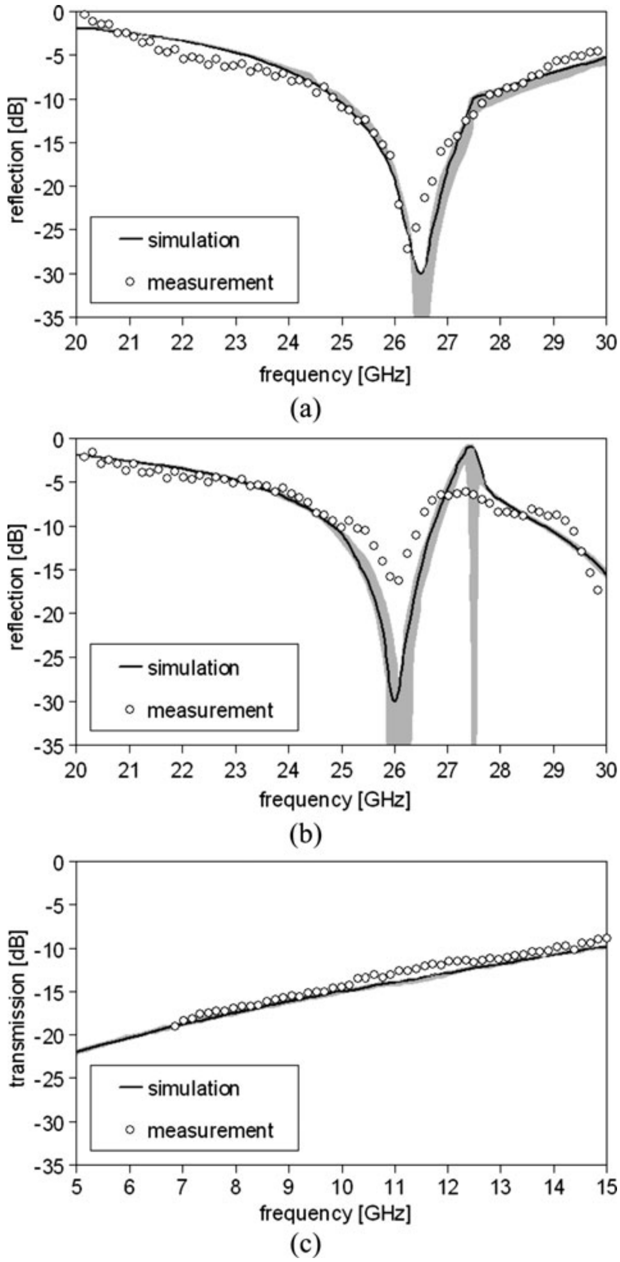

Fig. 7. Simulation (solid line), measurement (circles), and simulated tolerance analyses (light gray bands): (a) TE reflection coefficient in K band; (b) TM reflection coefficient in K band; and (c) TE transmission coefficient in X band.

good, with minor discrepancies mainly due to unavoidable small inaccuracies in the alignment of the measurement setup and to the fact that the prototype is not perfectly flat because of the manufacturing mechanical stress.

In addition, for TM polarization, a discrepancy between simulation and measurement is observed around 27.5 GHz, and it is attributed to the finite dimension of the mirror and the absorbing material around it, which dumps the higher-order Floquet modes near their cut-off.

In X band the agreement between simulations and measurements can be considered excellent. Please note that TM simulations and measurements for the X band are not reported in Fig. 7(c) for clarity, they being practically indistinguishable from the TE curves, as shown in Fig. 4.

Both in X and K bands it is evident that the manufacturing accuracies previously reported determine almost negligible tolerance bands. However, for the sake of completeness, the impact of the manufacturing tolerances has also been analyzed at an antenna level. In particular, a representative set of dichroic mirrors, with aperture diameter d and separation s generated according to the tolerances curves shown in Fig. 5 have been modeled in the antenna analysis tool described in the previous section [11], and the overall antenna radiation patterns have been calculated. As expected, the variations with respect to the nominal case are negligible (i.e. maximum antenna gain reduction less than 0.1 dB).

IV. CONCLUSION

This paper reported the investigation of the punching technique, or metal stamping, as an alternative low-cost and fast manufacturing process suitable to fabricate all-metal dichroic mirrors. It represents a promising approach for future ground stations for space communication, based on arrays of many small reflector antennas, where the possibility of having several cheap units is crucial.

The most important advantage given by the punching technique is the cheap fabrication cost (at least 1/50 compared to standard milling technique according to authors' experience) and the fabrication speed (for a full-dimension final unit, a few hours compared to several weeks required by the milling), while maintaining a tolerance manufacturing accuracy comparable to more costly and time-consuming approaches. If the benefit in terms of cost is clear, it must be remarked that the fast fabrication process is also a fundamental feature, which permits one to strongly mitigate the risks associated to the fabrication itself (i.e. an out-of-spec unit can be promptly discarded after inspection with a moderate impact in terms of money and time loss).

The most relevant manufacturing constraints are related to the maximum plate thickness t and the minimum aperture separation s, which pose some limitations to the mirror design flexibilities. Nevertheless, when the optimum trade-off between electrical performance and manufacturing cost and risk is crucial, the punching technique results to be a good candidate.

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