Multi-layered Submillimetre FSS of Shifted Crossed Slot Elements for Applications in Radio Astronomy

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Abstract — This paper deals with the designs and performances of the multi-layered FSS structures proposed as band-pass filters in space applications. The so called shifted crossed slot elements are utilized as resonant meshes, with the help of which two types of 4-resonant-mesh-filters are realized either with air spacers or dielectric separations, possessing a sharp roll-off frequency response. The method of moment (MoM) used in a spectral domain analysis and some numerical results are presented. The production technology is also described.

I. INTRODUCTION

The advances in frequency selective surfaces (FSS) technology have led to their use as high-grade filters for submillimetre wave applications [1], [2]. In this paper, we report on the designs and performances of FSS band-pass filters which fulfill the special requirement of bolometer systems for radio astronomy. The proposed filters shall, on the one hand, exhibit a selectivity as high as possible, so it is often necessary to have a frequency separation ratio of 1.05:1 or less; on the other hand possess a broad stop band - a good attenuation is necessary particularly at higher frequencies because of the thermal radiation rising with $f^2$, from telescope and atmosphere at ambient temperature [3], [4].

![Fig. 1. Cascading of a high-pass, a low-pass and a band-pass](image1)

A sharp roll-off frequency response can only be achieved by making use of the interference effects between two or more FSS screens. We present one 4-resonant-mesh-filter with air spacer at a cut-off frequency of 290 GHz, and one with 4 mesh layers embedded in dielectric material (polypropylene), at a cut-off frequency of 370 GHz. The so called shifted crossed slot elements are applied as resonant mesh structure.

To suppress the high order propagating modes, a low-pass filter consisting of layers of metallic square patches is applied for making a sufficient wide stop band. On the other hand, a circular waveguide is employed as a high-pass which cuts out the undesired low frequency band to meet the required bandwidth. Fig. 1 indicates schematically this combination. It is easy to realize these types of low-pass and high-pass filters, therefore, the entire problem is led to the essential task of developing the band-pass filters with a sharp roll-off on the edge of interest (cut-off).

II. DESIGN OF FSS BAND-PASS FILTERS

In simple mesh filters, metal meshes (either free-standing or supported by dielectric sheets) are mounted with separating distances typically less than one wavelength. The distances between these meshes provide the resonant elements. More advanced designs use meshes that are resonant in themselves thus reducing the accuracy of spacing required [5], [6]. Fig. 2 shows a capacitive mesh, an inductive mesh and a resonant mesh of crossed slot structure.

![Fig. 2. (a) Capacitive mesh, (b) Inductive mesh and (c) Resonant Mesh](image2)

In this study, we take advantage of the so called shifted crossed slot elements to realize the band-pass filters because of their excellent resonant behavior. Fig. 3 illustrates the geometry of this resonant mesh and its equivalent circuit from lumped elements.

![Fig. 3. (a) Shifted crossed slots elements and (b) Equivalent circuit](image3)

It has to be taken into account during the design process that compared to the normal crossed slots elements (Fig. 2.
(c)), the densely packed shifted crossed slots elements cause a frequency shift towards higher frequencies. Furthermore, they possess a broader bandwidth that leads to more stability according to the frequency response. This has been confirmed by many measurements.

The multi-layered FSS band-pass filters are first approximated by an equivalent circuit model, which represents the FSS layers and their separations (air or dielectric) by LC resonant circuits and transmission lines, respectively (Fig. 4).

![Fig. 4. Equivalent circuit model consisting of LC resonant circuits connected by \( I = \lambda/4 \) transmission lines.](image)

The analysis of the equivalent circuit model is carried out with the help of the classical filter theory [7], [8]. The transmission characteristics of the equivalent circuits are evaluated recursively starting from the end of the circuit applying the formulas of transmission-line. This first order analysis shows that the roll-off rate is optimized by making the length of the transmission lines \( I = \lambda/4 \), where \( \lambda \) is the peak wavelength of the individual resonant circuits. The transmission lines then act as the so-called impedance inverters leading to high peak transmission in the pass band, but away from the center wavelength leading to a sharp cut-off and excellent out of band rejection.

For the realization of the filters with FSSs, a 4-resonant-mesh-filter design is selected - 4 identical resonant meshes are placed one on top of the other with an equal spacing layer of \( I = \lambda/4 \). The performances of the designed filters are further analyzed and the transmission characteristics are exactly calculated with the help of the below mentioned numerical code.

### III. Computation of the Transmission Factors

The computation of the FSS filter is based on a spectral domain analysis, which solves the electromagnetic field problem with the help of the spectral Green’s function of layered media [9].

![Fig. 5. General grid array consisting of a double periodic arrangement of elementary cells.](image)

Fig. 5 shows a general grid array, which consists of a infinite double periodic arrangement of elementary cells. In this study, they are apertures in a conducting surface. In the \( j \)th layer, the position of the \( pq \)th cell compared to that of the unit cell is described by

\[
\mathbf{r}_{pq} = \mathbf{r}_{1j} + q\mathbf{r}_{2j},
\]

where \( I \) denotes the layer number. And the \( pq \)th cell is move by

\[
\Delta x_{pq} = p \cdot r_{1j}x + q \cdot r_{1j}x, \quad \Delta y_{pq} = p \cdot r_{1j}y + q \cdot r_{1j}y
\]

from the unit cell located in the origin. Applying the Floquet theorem, the magnetic current distribution is formulated:

\[
\mathbf{M}(x, y, z) = \sum_{l=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} U_{ln} \cdot \mathbf{F}_{ln}(x - \Delta x_{pq}, y - \Delta y_{pq}) \cdot e^{i(k_{ex}\Delta x_{pq} + k_{ey}\Delta y_{pq})\delta(z - z_{l})},
\]

where \( \mathbf{F}_{ln}(x, y) \) are the basis functions, \( k_{ex} \) and \( k_{ey} \) are the wave numbers of the incident plane wave, and \( U_{ln} \) are the unknown amplitudes of magnetic currents, respectively.

Using the 2-D Fourier transformation, the magnetic field is obtained as

\[
\mathbf{H}(x, y, z) = \sum_{l=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} \frac{1}{r_{1j}x \cdot r_{1j}y - r_{2j}x \cdot r_{1j}y} \cdot \frac{2\pi}{r_{1j}x \cdot r_{2j}y - r_{1j}y \cdot r_{1j}y} \cdot \mathbf{M}^H_{\mathbf{M}}(k_x(l, p, q), k_y(l, p, q), z, z' = z_{l}) \cdot \mathbf{F}_{ln}(k_x(l, p, q), k_y(l, p, q)) \cdot e^{i(k_{ex}r_{pq} + k_{ey}r_{pq})},
\]

where \( \mathbf{M}^H_{\mathbf{M}} \) denotes the spectral Green’s function for the magnetic field, \( \mathbf{F}_{ln} \) are the Fourier transforms of the basis functions \( \mathbf{F}_{ln} \) and the discrete wave numbers

\[
k_x(l, p, q) = k_{ex} + \frac{2\pi}{r_{1j}x \cdot r_{1j}y - r_{2j}x \cdot r_{1j}y} \cdot (r_{2j}y \cdot p - r_{1j}y \cdot q)
\]

and

\[
k_y(l, p, q) = k_{ey} + \frac{2\pi}{r_{1j}x \cdot r_{1j}y - r_{1j}y \cdot r_{1j}y} \cdot (r_{2j}x \cdot p - r_{1j}x \cdot q)
\]

are in context with the Floquet theorem.

An integral equation for the magnetic currents can be formulated by substituting the spectral domain representation of the magnetic field (eq. 4) into the remaining boundary condition at the surfaces. The integral equation is solved by the Galerkin MoM, leading to a linear system of equations with the system matrix \( [Z] \) and the matrix elements

\[
Z_{mn}(l, l') = \frac{1}{r_{1j}x \cdot r_{1j}y - r_{2j}x \cdot r_{2j}y} \cdot \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} \mathbf{M}^H_{\mathbf{M}}(k_x(l', p, q), k_y(l', p, q), z = z_l, z' = z_{l'}) \cdot \mathbf{F}_{ln}(k_x(l', p, q), k_y(l', p, q)) \cdot \mathbf{F}_{lm}(l, p, q) - k_y(l, p, q).
\]

A computer program on the basis of this theory has been developed. A lot of FSS structures have been calculated and a large number of measurements have been made, yielding a rather good agreement between the measured and the calculated values [4], [9].
IV. Fabrication

Basic parts of the filters are the meshes which are galvano formed high-precision parts (Fig. 6). They consist of approximately 15 micron thick Ni-foils holding an appropriate array of apertures (in our case the array consists of a dense packing of cross-shaped apertures). Even for structured regions of 100 mm diameter or more the thin foils exhibit an excellent flatness and at the same time a high mechanical stability. Both are necessary for the embedding in a polymer. Up to four meshes were stacked together in well-defined distances and embedded in a polypropylene matrix.

The idea behind the embedding is the following: Knowing the spectral behaviour of a single mesh, it is possible to match a desired spectral profile by stacking several meshes with specific spacers between them. This can be done with help of annuli between freestanding plane meshes: the thickness of the distance-ring is equal to the air-gap between two adjacent meshes. The spectral performance of such filters is strongly depending on the dimension of the spacer, so it is not wonder that small changes in the distance between the meshes cause severe changes (typically degradations) of the achieved spectral profile.

We are considering filters of large diameter, and these filters are to be used in cryogenic systems. Consequently, the filters have to withstand repeated vacuum cycles and repeated thermal cycles. Considering large filters of freestanding meshes with air-spacers between them, already a single vacuum cycle (air-vacuum-air) is a substantial load at least onto the outer meshes of the stack. During cryogenic cycles the large meshes are cooled or warmed radially, accordingly different regions of the meshes have different temperatures and hence different thermal contractions. Especially when repeated, both cycles result in a degradation of the evenness of the meshes, and this is equivalent with a loss in the optical performance.

Embedding the meshes into an appropriate medium is a way to make the filters so robust that they withstand vacuum cycles as well as thermal cycles. For this purpose we use commercial PP-foils which are available in a large variety of thickness. The desired PP-spacer thickness can be realized by combination of several thin foils. Then beginning with a thin PP-foil the stack starts with the first mesh, then the first PP-spacer in form of several foils follows, then the second mesh and so on. The single meshes are (more or less) aligned to each other. After the last mesh a last thin foil is added as top layer. Then the complete stack is put between two heating plates which are transferred into a vacuum chamber. Here the stack of many foils is gently heated above the melting temperature of the polypropylene. After cooling all single foils have combined into a flat monolithic block of polypropylene incorporating several meshes in well-defined distances. The resulting filters are very plane, at room-temperature as well as at low temperatures. When cooling to temperatures around 4 K the composite filter might deform due to differences in the thermal expansion coefficients of its components. Because most of the integral thermal contraction has happened already at 77 K, we therefore performed thermal cycles by dropping the filters into liquid nitrogen and bringing them back to room-temperature. In spite of this rough method the filters showed no change (visual inspection) or degradation (spectral measurement) over 40 cycles. Thus, embedding these particular meshes into polypropylene results in rigid and robust filters for cryogenic application and provides stable optical performance over a long lifetime.

V. Numerical and Experimental Results

Numerical and measured results of two types of band-pass filters composed of the shifted crossed slot elements are presented. The element sizes and the free-standing mesh resonant characters of the two different types are displayed in Fig. 7 and Fig. 9, respectively. Fig. 8 shows the 4-resonant-mesh-filter in air, i.e. type 1, designed for $f_c = 290 \text{GHz}$, and Fig. 10 the type 2 of $f_c = 370 \text{GHz}$ with dielectric separations. A good agreement is achieved between the measured and computed values. The filter type 1 gives an edge of band frequency roll-off rate of ~1.05:1. However, due to the attenuation in the pass band of the filter type 2, the absorption loss of the substrate material has been shown to be a limiting factor in the performance.

![Fig. 7. Computed and measured transmission of one free-standing resonant mesh of type 1.](image)

Grid parameters are: $g = 935 \mu m$, $d = 760 \mu m$, $w = 99 \mu m$. 
VI. CONCLUSION

The work presented in this paper describes design and performance of submillimetre band-pass filters, which are realized by shifted crossed slot elements meshes. Some numerical results are presented, which agree quite well with the experimental measurements. The performance of a multi-layered FSS with dielectric spacer material is limited by the insertion loss, which has negative influence on the transmission roll-off rate. Further developments are in progress to reduce this loss component.

REFERENCES