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# Design of Frequency Selective Windows for Improved Indoor Outdoor Communication

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**Abstract**

The use of low emissivity windows degrades radio communication. This paper presents design, manufacturing and test measurements for an energy saving window that is transparent to GSM, GPS and 3G radio wave frequencies. A frequency selective structure (FSS) is used in the metallic coating of the window to provide the needed transparency that ranges from 900 MHz to 2 GHz. The periodic pattern used for the FSS is of the aperture type and the elements are hexagon loops. FSS simulations are performed using two different methods, namely the mode matching technique and the Finite-Difference Time Domain method. A frequency selective window is manufactured from a commercially available low emissivity glass. Measurements indicate that the frequency selective window shows an improvement of at least 10 dB in the transmission over the original window.

# 1 Introduction

The use of a very thin metallic coating in modern window design is an extremely effective way to save energy. Acting as a filter, the shielding blocks the electromagnetic radiation in the infrared region and is completely transparent to the visible part of the spectrum, thus rejecting the heat outside of a building during the summer and keeping the heat inside during the winter. These special windows are called low-emissivity (or energy saving) windows since the metallic oxide layer present in the window reflects a significant portion of long and short infrared wave energy [6, 9, 14]. They are commercially available at large scale and used in many new buildings and vehicles. From a communication point of view, there is a subsequent problem with the use of such technology: the electromagnetic radiation in the microwave region is blocked and the blocking gets more intense as frequency increases. This means that wireless communication is severely restricted into and out from buildings. This can be an advantage for Wireless LANs since spectrum re-use can be increased by creating small isolated zones and privacy can be obtained by delimiting the space of use. However, for GSM, GPS, and UTMS transparency is needed to be able to use these services inside buildings.

A solution to this problem is to create a Frequency-Selective Structure (FSS) in the metallic coating of the low-e glass. This structure is a periodic array of apertures removed from the window coating. The structure behaves like a band pass filter and is tuned to a bandwidth that covers the frequencies for GSM, GPS and UMTS (900-2200 MHz), without degrading the thermal response of the window [6, 9, 14].

The FSS is an array of periodic apertures in a conductive surface that, when illuminated by an electromagnetic wave, exhibits total transmission around the resonance frequency [4, 8, 12]. The planar two-dimensional periodic structure proposed in this paper is made of hexagonal loop elements, since such a structure has a large bandwidth and relative weak incident angle dependence. There are many numerical methods to simulate the response of an FSS. The methods used in this paper are

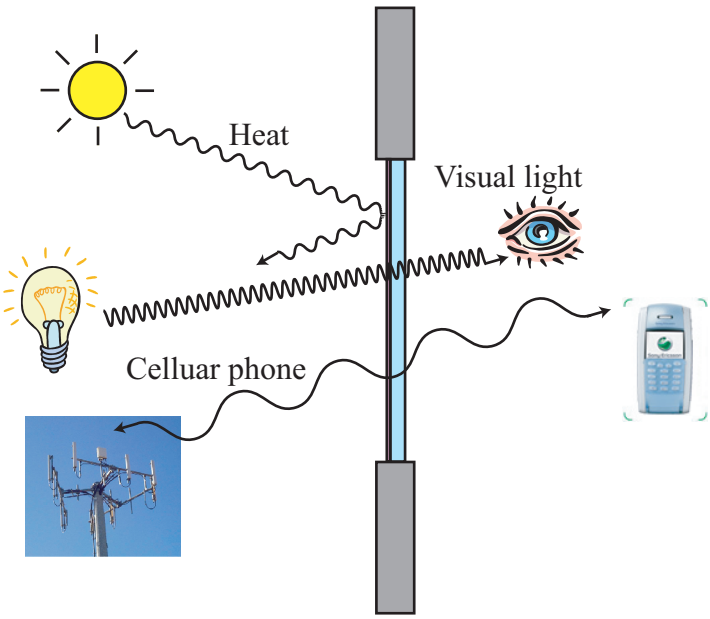


**Figure 1**: Illustration of a frequency selective window. The infrared radiation (heat) is blocked by the window, but the indoor outdoor communication is possible. The visible part of the spectrum remains unchanged.

the mode matching technique used in conjunction with the Finite Element Method (FEM) and the Finite Difference Time Domain (FDTD) method.

The next section is a review of different types of low-emittance windows and their electromagnetic properties. In section 3, frequency selective structures are described and the different FSS types and element shapes are presented. The commercial windows and different manufacturing processes are described as well as the improvement of the frequency selective windows over normal low-e windows from a radio communication point of view. The FSS parameters are studied in section 4. The geometry of the elements, the periodicity of the array, conductivity and thickness of the metallic layer and permittivity of the dielectric layer are also discussed. Finally, section 5 describes the manufacturing process as well as the results of measurements for the FSS window.

## 2 Low-emittance windows

The standard type of window pane is made of non-magnetic glass with a typical conductivity of $\sigma = 10^{-12}\,\mathrm{S/m}$, a relative permittivity $\epsilon_r \approx 4$, and a thickness of $l \sim 4\,\mathrm{mm}$. The pane presents no major obstacles to microwave radio propagation, since it is thin compared to the wavelength and its conductivity is extremely small. The panes are transparent for more or less all radiation with frequencies below UV light. Thus a window pane is transparent for visible light (390 to 770 nm), infrared (IR) light (770 to 2100 nm) as well as microwaves. The transparency of IR light is during summer and winter unfavourable. By using energy saving windows, one

can improve thermal response leading to an economically viable solution. Low-emittance (low-e) windows consist of a microscopically thin, practically invisible coating deposited on the surface of the window pane. The coating is made of metal or metallic oxide and improves the thermal performance by reducing the solar heating, *i.e.*, it reflects a significant portion of the infrared radiation. One drawback with these energy saving windows is the degrading of the radio channel properties. For a commercial low-emittance window, the metallic oxide coating provides 20 dB to 35 dB of transmission damping in the frequency range 1-2 GHz.

There are two types of low-e windows [2]: Hard coat low-e and soft coat low-e. Hard coat low-e, or pyrolytic coating, is a coating applied at high temperatures and is sprayed onto the glass surface during the float glass process. The coating is relatively durable, which allows for ease of handling and tempering. Soft coat low-e, or sputter coating, is applied in multiple layers of optically transparent silver sandwiched between layers of metal oxide in a vacuum chamber. This process provides the highest level of performance and a nearly invisible coating, but is a more expensive alternative than the hard coat low-e glass.

In this paper, both types of low-e windows are analyzed, but the FSS was only applied on the soft coat window. In Section 5 measurements are made on both windows. The soft coat window was provided by Glaverbell (Planibel) [3] and the hard coat by Pilkington (K-Glass) [10].

# 3 Frequency Selective Structures (FSS)

A Frequency Selective Structure (FSS) is defined as an array of periodic apertures perforated on a conducting sheet or metallic patches in a substrate. These structures resonate at a given frequency and attain spectral selectivity [13, 14]. There are two fundamental types of FSS. The first consists of the metallic patches on a substrate. This configuration is commonly referred to as capacitive FSS and has a low-pass filter behavior. The other fundamental type consists of apertures on a metallic sheet. It behaves like a high-pass filter and is referred to as an inductive FSS. If the configuration of the elements have resonance characteristics, the capacitive FSS behaves like a band-stop filter around the resonance frequency and the inductive behaves like a band-pass filter [1]. In the present application, the inductive FSS is used since a band-pass structure is desired.

In this paper two different methods are used to simulate the behavior of frequency selective structures. The first is the mode matching technique combined with the Finite Element Method (FEM) [12], and is used when the metallic coating is assumed to be perfectly conducting. The second is the Finite Difference Time Domain (FDTD) method [11], and is used for coatings with finite conductivity.

FSS behavior can be divided into four frequency response types: low pass, high pass, band pass and band stop as shown in Figure 2. The low pass FSS and the high pass FSS are complementary surfaces in the sense that they together cover the entire surface. According to Babinet's principle, the transmission and reflection coefficients of one surface will be the reflection and transmission coefficients of the

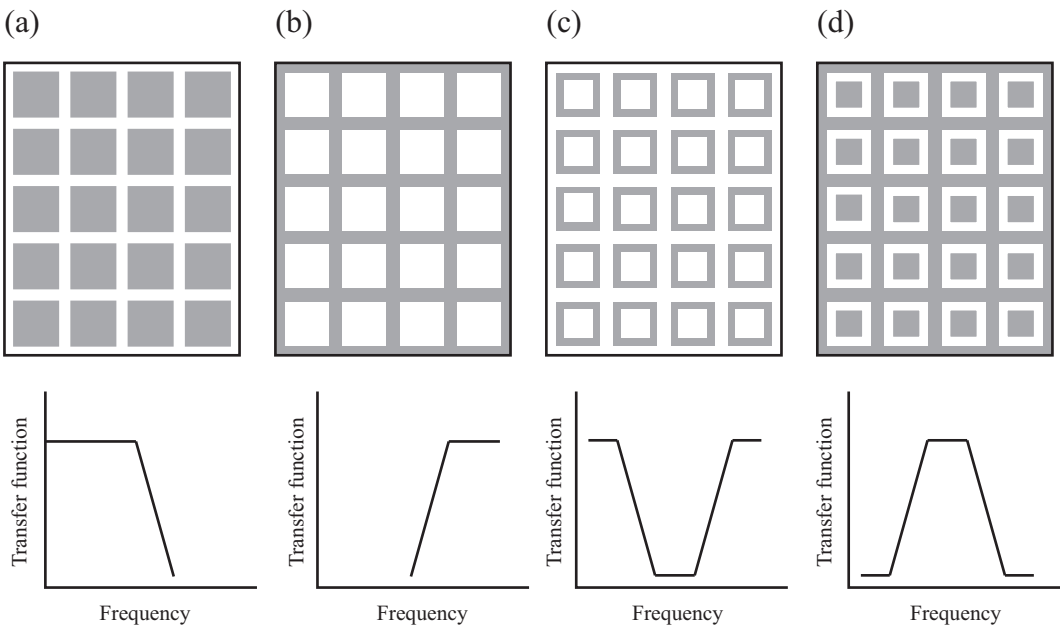


**Figure 2**: Typical FSS types and their responses. The gray surface represents a metallic surface. a) array of metallic patches and respective low pass behavior, b) apertures on the conductive medium and ideally high pass transfer function. Figures c) and d) show the loop elements that have resonant characteristics. c) metallic loop and d) aperture loop.

other. That implies that a high pass FSS is obtained from a low-pass FSS by exchanging the conductive parts with the non-conductive parts. This applies also to the band-pass FSS and band-stop FSS. However, the surface must meet certain requirements. First, screen thickness should be less than $1/1000\lambda$ (infinitely thin) and there should be no dielectric layer. When a layer of dielectric is added to a metallic FSS, the resonant frequency decreases.

Figure 2a, depicts a periodic array of conducting elements (gray squares) that attains a low-pass characteristic. By using Babinet's principle, the characteristic in Figure 2b is obtained by simply reversing the materials. Using the same principle, the band-pass filter shown in Figure 2d has a structure that is the complement of the structure for the band-stop filter in Figure 2c.

The element shape is crucial when designing an FSS. They can be divided into four major groups, as described in [7]. The element adopted in this paper is the hexagonal loop, due to its large bandwidth and stability to different incident angles and polarizations. It should be noted that stability to angle of incidence and polarization depend even more on the dielectric than on the element. A careful design of an FSS with several dielectric slabs can provide independence of polarization and angle of incidence [7]

The conductive FSS can be divided into "thick" or "thin", depending on the frequency for which it is designed. If the thickness of the FSS is less than $0.001\lambda$, where $\lambda$ is the free-space wavelength, the FSS is considered to be thin. A thin

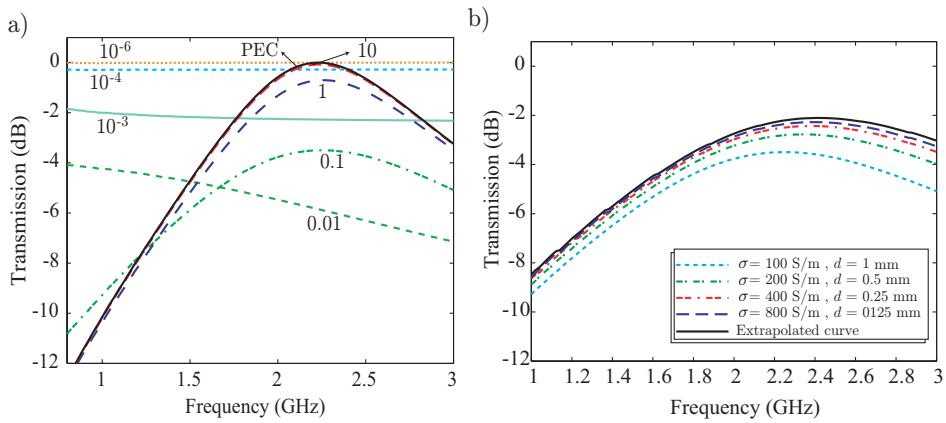


**Figure 3**: Dependence of the transmission response for a hexagonal FSS of the conductivity. a) different $\sigma d$ where $d = 1\,\mathrm{mm}$. As $\sigma d$ decreases, the frequency selective behavior of the structure fades away. b) Transmission response for constant $\sigma d = 0.1\,\mathrm{S}$. The results approach the solid curve that was obtained by extrapolation.

FSS is accurately modeled as "infinitely thin" in numerical simulations. If the thickness exceeds $0.001\lambda$, the structure is considered "thick". The conductivity of the structure can be approximated by a perfectly electric conducting (PEC) plate if materials with high conductivity like copper are used. If the material is not a metal with high conductivity, the FSS performance degrades and the PEC approximation is not applicable. In order to examine the significance of thickness and conductivity for the transmission of microwaves, two types of numerical simulations of an FSS with finite conductivity were carried out. The structure was a hexagon pattern with thickness of one grid cell along the $z$-direction. On each side of the structure an Absorbing Boundary Condition (ABC) was placed at a distance of $0.5\lambda$ from the structure, in order to truncate the domain for the FDTD calculations.

In Figure 3a, transmission for different values for $\sigma d$ are depicted when $d$ is fixed and $\sigma$ is altered. With a perfectly conductive surface (PEC), the FSS has a strong resonance around 2.4 GHz. The curve for a conductivity of $\sigma = 10^4\,\mathrm{s/m}$ is almost on top of the PEC curve which indicates that PEC is a good approximation when the conductivity is high. However, as $\sigma d$ decreases, the resonance fades away and the surface ceases to be frequency-selective. Eventually, when the conductivity is extremely small, the structure behaves like a dielectric plate.

In the second case simulations were performed for a constant $\sigma d$ when both $\sigma$ and $d$ are altered. Due to the well defined points in space required by the FDTD method, the thickness of the conductive layer is altered by reducing the grid cell in the $z$-direction. The corresponding transmission curves are shown in Figure 3b. The transmission response tends to converge when the thickness of the conductive layer is considered thin. An extrapolation to zero grid size was performed to predict the response of the "infinitely thin" case. The extrapolation is first-order accurate and was made with `polyfit`, a built-in function of MATLAB.

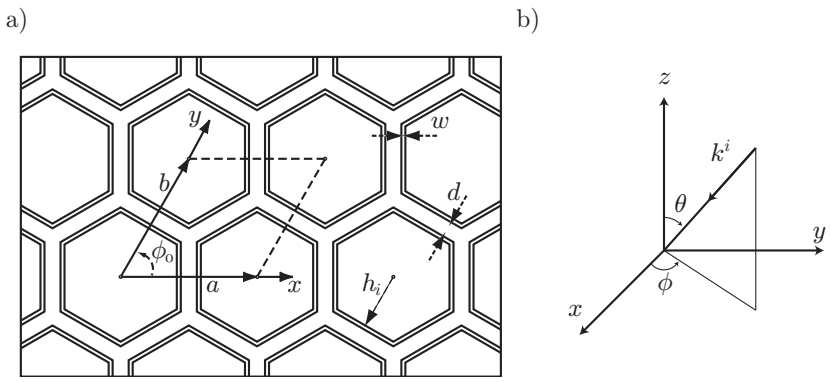


**Figure 4**: a) The hexagon geometry. $a$ and $b$ are the periodicities along the $x$ and $y$ axis, respectively, $h_i$ is the height, $t$ the width, and $d$ the distance between elements of the hexagon. Only one unit cell is represented. The structure is made of a dielectric layer and an aperture layer. b) The wave vector of a plane wave incident on the FSS.

# 4 Design of an FSS window

The main purpose of this paper is to propose designs of commercial low emissivity windows transparent to mobile communications. Such frequencies include GSM that operates in 900 MHz, 1800 MHz and 1900 MHz, Global Positioning System (GPS) working around 1500 MHz, and 3G operating around 2 GHz. The required bandwidth ranges from 900 MHz to 2 GHz. This section presents the design of an FSS window, based on hexagon elements. The hexagons are chosen due to their superior bandwidth and stability to different incident angles and polarization [4, 7, 15]. Due to lack of specific information, an assumption had to be made on the dielectric properties, as well as the conductivity and thickness of the metal oxide coat in the glass. Several simulations were made to investigate how the transmission curves depend on the parameters of the elements. These simulations are performed at different angles of incidence and different polarizations. Also the influence of the metallic-layer conductivity and the glass permittivity on the pass band was studied. Finally, the design was fully optimized for bandwidth when the parameters are restricted to match a milling machine that mills the pattern in the metal oxide layer of the glass. The numerical calculations are mainly made using a mode-matching technique in conjunction with the FEM. The Finite Difference Time Domain (FDTD) approach was also used to analyze the loss in the conductive medium. All the simulations with the mode matching technique program were made with the number of Floquet modes set to 5 to provide accurate results [15].

## 4.1 Parameter Study

The parameters that can be optimized to shape the transmission response in the microwave region, are directly related to the element itself. These include the element's height, width and periodicity. For the typical soft coat window, a relative permit-

tivity of $\epsilon_r = 4$ and a glass thickness of 4 mm were assumed. The mode matching technique requires infinite conductivity for the aperture layer and the thickness of the aperture is known to be extremely small. The elements are placed in a grid as shown in Figure 4. The grid is infinite in the $xy$-plane and the $z$ axis is orthogonal to the FSS surface. Each element was spaced periodically along the $x$ axis with period $a$. The $y$ axis makes an angle $\phi_0$ with the $x$ axis and the elements are spaced along this axis with period $b$ [15]. In this case, $\phi_0 = 60°$ and $a = b$. For a better understanding of the simulations, these parameters are replaced by the height of the inner hexagon $h_i$, the width of the loop $w$ and the distance between hexagons $d$, *cf.* Figure 4. In order to model the window accurately, two layers were added. The first one was the dielectric layer and the second an aperture layer, see Figure 4. The incident electromagnetic waves are plane waves with known direction of propagation and polarization, *cf.* Figure 4b.

## 4.2 Hexagon Parameters

A starting point to design an FSS surface is to calculate the approximate wavelength at which the elements on the structure resonate. The hexagonal loop resonates approximately when its average circumference equals a multiple of the vacuum wavelength, $\lambda_r \approx 2\pi r$ or $\lambda_r \approx 2\pi(r + w)$ [4, 15], where $r$ is the average radius and $w$ is the width of the loop. Using the first equality, a resonant frequency centered at 1.9 GHz yields a radius of $r \approx 25$ mm, and an inner height of $h_i \approx 22$ mm. A width of the loop of $w = 1$ mm and a distance between elements of $d = 4$ mm is considered. The structure resonates at approximately 1.75 GHz. By adding a dielectric surface on one side of the FSS the resonance $f_0$ is shifted downwards to approximately $f_0/\sqrt{(\epsilon_r + 1)/2}$ [7]. This shift is compensated by a scaling of the height of the hexagon in order to keep the resonance at the same frequency. In the next simulations the inner height, $h_i$, of the element is the variable. The other parameters are as in the previous simulation, *i.e.*, $w = 1$ mm and $d = 4$mm. Figure 5(a) plots the transmission response for TE and TM polarization with 1° of incident angle. The bandwidth is stable for both polarizations. The only significant changes appear as a shift in the resonant frequency. It is evident that the radius of the hexagon is directly connected to the resonant frequency. The mismatch of the resonant frequency for the different polarizations of the TE and TM modes at 1° of incident angle is due to the different periodicity of the structure along the horizontal and vertical axis.

The effect of the width of the hexagon, $w$, was analyzed by keeping the inner height of the element at $h_i = 14$ mm. The resonance frequency is $f_0 \approx 1.9$ GHz. The simulations show that the transmission response do not change significantly with a variation of the width. The width was then kept small in order to minimize the transmission of infrared radiation. The fraction of removed material $p$, for the hexagon geometry, is given by:

$$p = \frac{4w(w + 2h_i)}{(2w + d + 2h_i)^2} \tag{4.1}$$

The percentage of removed material for $w = 0.5$ mm and $w = 1$ mm, for example,

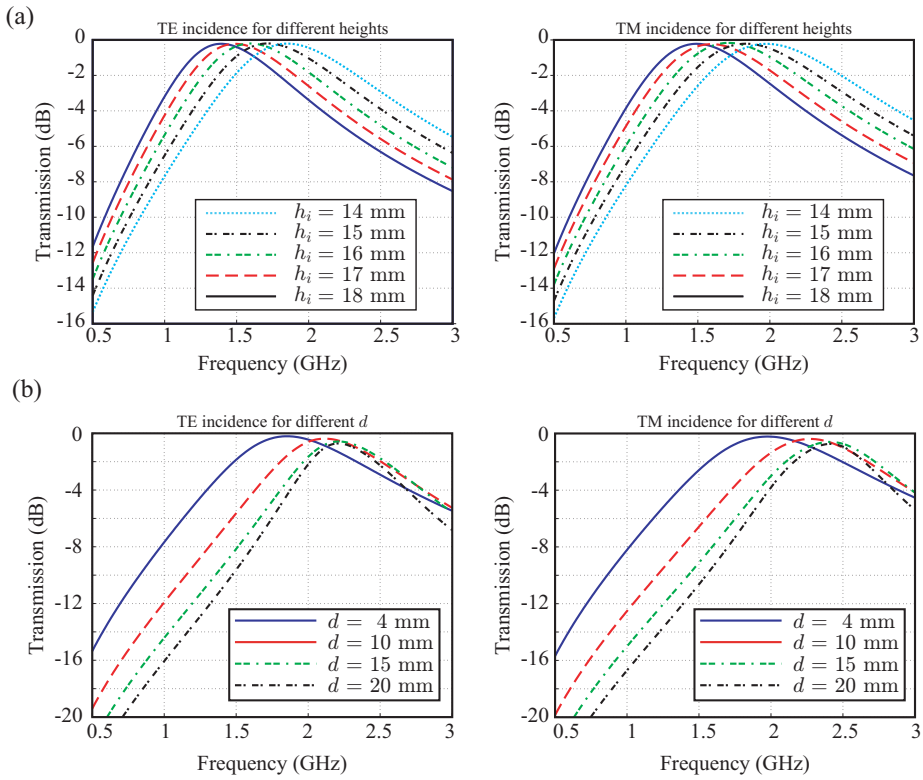


**Figure 5**: Transmission response for different parameters of the hexagon.

is $p = 5.2\%$ and $p = 10\%$, respectively. A set of simulations were also performed where the distance between the elements was increased from $d = 4\,\text{mm}$ to $20\,\text{mm}$ with the other parameters fixed. Figure 5(b) plots the corresponding transmission curves.. The resonance shifts upwards and the bandwidth decreases significantly as the distance $d$ increases. The effect of different incident angles was studied by simulating an FSS with $h_i = 14\,\text{mm}$, $w = 1\,\text{mm}$ and $d = 4\,\text{mm}$. Figure 6 depicts the transmission curves for different incident angles, for both TE and TM cases. For the TE case, there is a decrease in bandwidth, especially at larger incident angles. For the TM case, the decrease is more accentuated and there is a null approaching the desired frequency range for larger incidence angles. Considering that the dielectric cannot be shaped, the resonance frequency is quite stable. In a real communication situation, incidence is present from all angles, due to the multi-path propagation of microwaves. To quantify the benefit of the FSS from a communication point of view, the incident angle has to be included in the analysis. The transmitted power is related to the incident power by

$$P_{\text{tr}} = |T|^2 \, P_{\text{in}} \tag{4.2}$$

where $T$ is the global transmission coefficient of the FSS structure. Consider an example where the incident power is equally divided into five discrete paths corresponding to the incident angles $\theta = [1°, 15°, 30°, 45°, 60°]$. The transmitted power

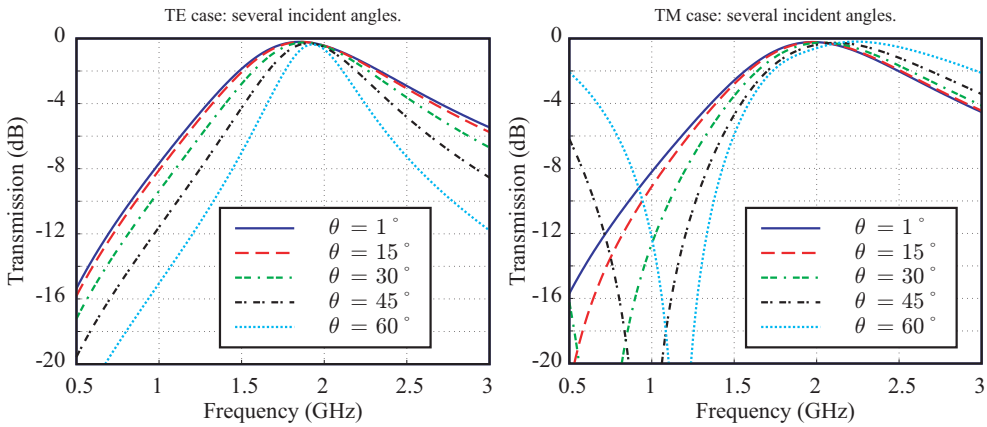


**Figure 6**: Transmission curves as a function of frequency for different incident angles for a hexagon geometry $w = 1\,\text{mm}$, $h_i = 14\,\text{mm}$, and $d = 4\,\text{mm}$. The resonant frequency stays fairly stable with the change of incident angle.

coefficient is then given by

$$\frac{P_{\text{tr}}(f)}{P_{\text{in}}} = \frac{\sum_n \cos(\theta_n)\,|T(\theta_n, f)|^2}{\sum\limits_n \cos\theta_n} \tag{4.3}$$

Figure 7b shows this coefficient of transmitted power for the FSS configuration with $h_i = 14\,\text{mm}$, $w = 1\,\text{mm}$ and $d = 4\,\text{mm}$. There is a major improvement of the transmission compared to the window without FSS over the bands of interest, considering that the metal oxide coating provides 20 dB to 30 dB of attenuation. A further improvement can be obtained by centering the percentage of transmitted power so that the transmission loss is the same at 900 MHz and 2 GHz.

## 4.3 Window parameters

The dielectric has a profound effect on the overall response of the FSS. By a proper design of the dielectric a structure that is independent of polarization and incident angle can be obtained. Such a structure has more than one FSS that are placed between carefully chosen low permittivity dielectrics [7]. In the case of windows, there is unfortunately hardly any freedom in the design of the dielectric structure. The window pane has a thickness of 4 mm and a given permittivity. Since the permittivity may differ between different types of window panes it is important to investigate the influence it has on the transmission. Figure 7 depicts the transmission response for different permittivities and it reveals a significant variation in the resonance frequency as well as in the bandwidth.

As mentioned before, the conductivity of the coating is of importance for the transmission properties of the FSS. To simulate the transmission response of a structure with different conductivities, the Finite-Difference Time Domain is used. The transmission curves are similar to the curves obtained in section 3. The conductivity is responsible for the spectral selective behavior of the structure. For coatings with

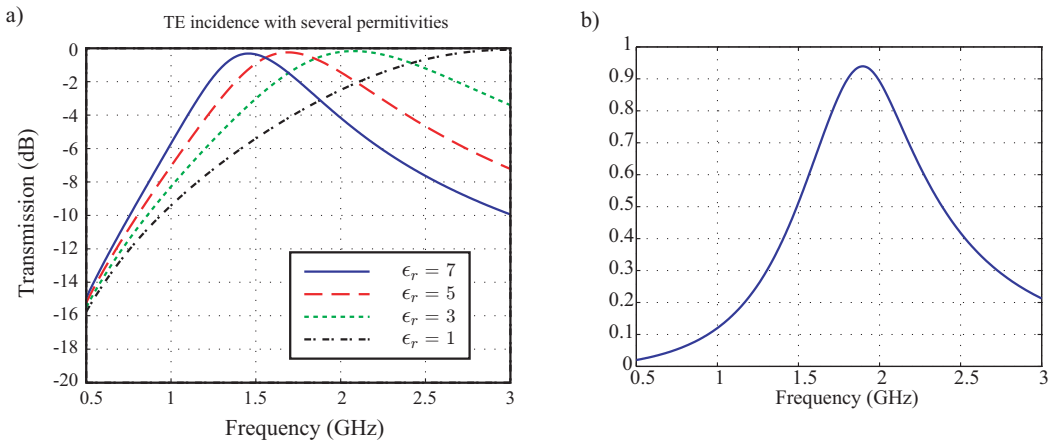


**Figure 7**: a) Transmission curve for different permitivities of the dielectric substrate. The hexagon geometry is given by $w = 1\,\text{mm}$, $h_i = 14\,\text{mm}$, and $d = 4\,\text{mm}$. b) Fraction of power transmitted through the FSS.

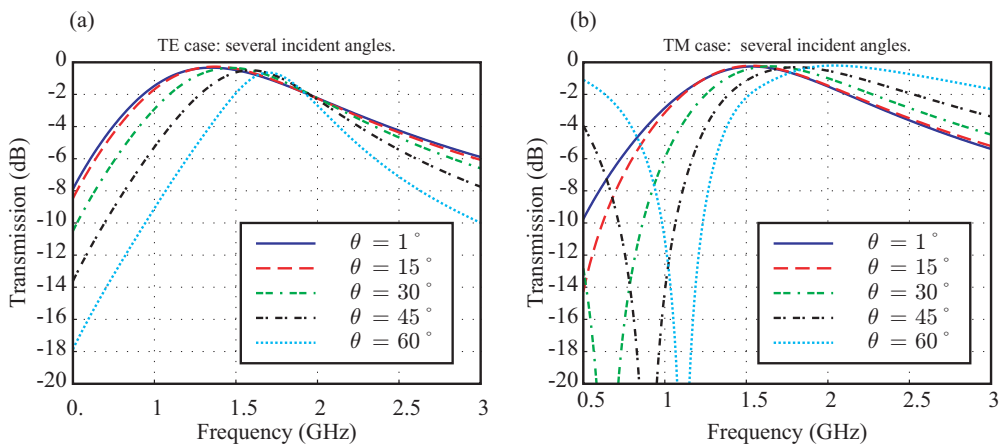


**Figure 8**: Transmission curves for the final hexagonal aperture FSS design. (a) TE case, (b) TM case.

high conductivity, the structure has a strong resonant frequency at 1.6 GHz. As the conductivity decreases, the resonance fades, and the structure no longer behaves like an FSS.

# 5 Measurements

In order to perform measurements, a window pane with an FSS was manufactured. A low-e glass window pane was chosen for this purpose. The hexagonal FSS was milled in the coating with a milling machine. The parameters of the hexagon were adjusted to the machine and to the dimensions of the cutter. In good conditions, the cutter can mill slits with a minimum width of 0.2 mm. A soft coat window with size of $40 \times 40\,\text{mm}$ was used. The parameters of the FSS were optimized, as described

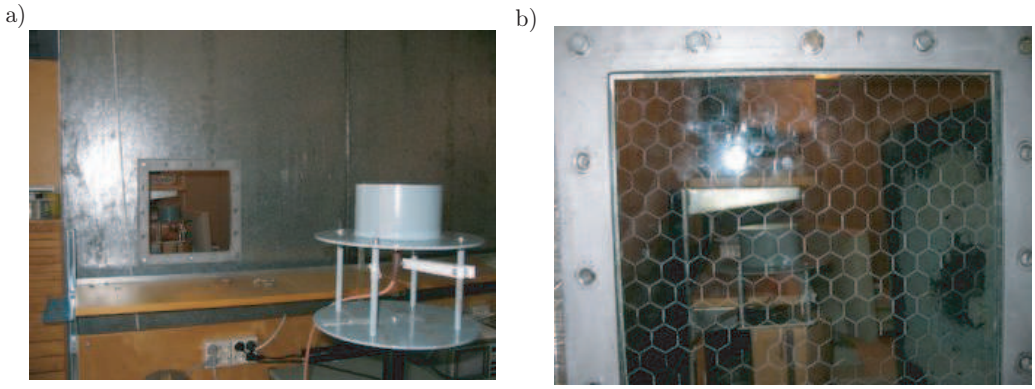


**Figure 9**: The measurement setup. a) The omni-directional antennas are placed in *line-of-sight*, one inside the shielded chamber and the other outside. b) The soft coated window with the drilled hexagons. Some glass was removed while making the slits because the milling machine does not have the needed precision to remove the extremely thin metallic coating. The hexagonal slits are not uniform due to the different depths in which the window was submitted, when the cutting was performed.

in the previous section. The spacing between elements was $d = 0.8\,\text{mm}$, the inner height $h_i = 9.3\,\text{mm}$ and the thickness of the loop $w = 0.2\,\text{mm}$. This design yields 3.8% of removed material and a bandwith of $B_{3dB} = 1.2\,\text{GHz}$ as shown in Figure 8.

The milling machine used a 36 mm long LPKF universal cutter for milling isolation channels and for engraving front plates [5]. This cutter can cut a line with a width of 0.2 mm. The cutter performed sufficiently well and it was used to process the whole window. The process of removing the hexagonal slits of the coating suffered from several problems. The cutting depth started with a depth of 0.05 mm, but approximately at the middle of the window, the machine had to be adjusted for a depth of 0.2 mm, since the cutter was seriously damaged. This resulted in a non homogeneous periodic pattern, with slightly different hexagonal elements in different parts of the window. Figure 9 shows that the hexagon elements can be visually observed since the thickness of the oxide layer is microscopically thin, and the machine removed glass material when performing the cutting. The result was far from perfect, however it was accurate enough to show the concept.

A simple measurement was made on the window, using a shielded chamber with a $30 \times 30\,\text{mm}$ aperture. Two identical omni-directional antennas operating in the $1\,\text{GHz} - 12\,\text{GHz}$ range were used as well as one network analyzer. The transmitting antenna was set 1.2 m away from the aperture in the chamber and the receiving antenna on the other side at 0.4 m from the window. Both antennas were at the same height and in *line-of-sight* as shown in the Figure 9a. Aluminum foil was used on the sides of the different glasses to improve the contact with the chamber. Measurements with five different devices were made: first the metallic plate that covers the chamber, then the soft coat window, then the soft coat window with FSS, then the hard coat window, and finally, just the aperture to normalize the measurements. The measurements were made twice to confirm the results.

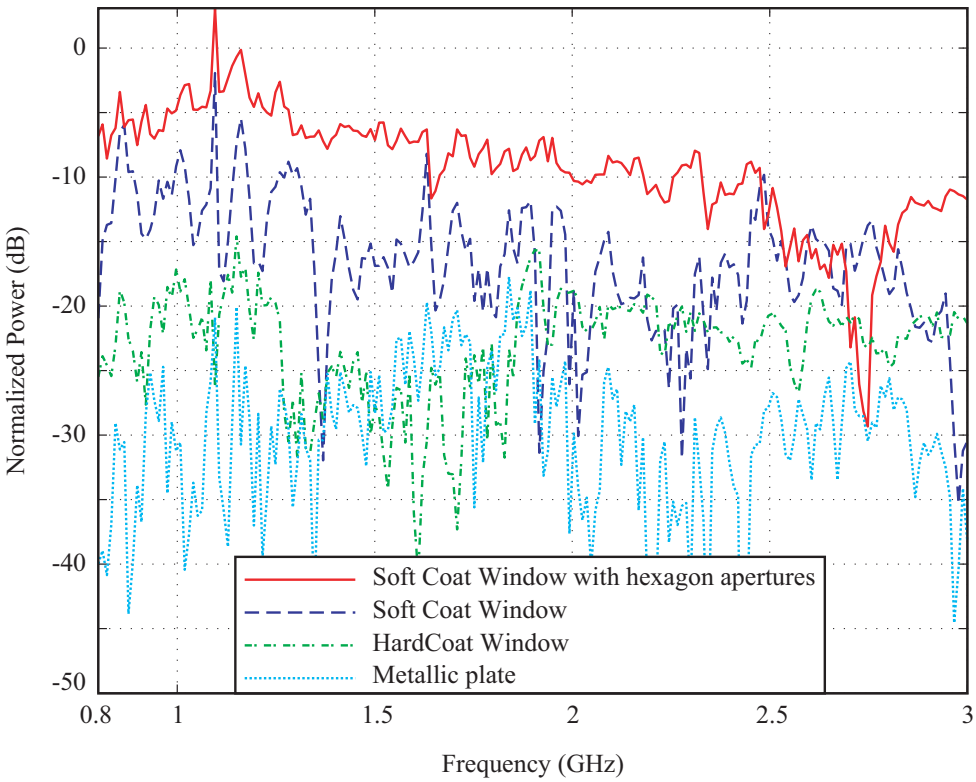


**Figure 10**: Four measurements are depicted: Soft coat window with hexagonal apertures on the metallic coating provide a improvement of 10 dB in the transmission power over the same window without the apertures. The hard coat window has a higher damping than the soft coat window in this frequency range, especially between 1.4 GHz and 1.9 GHz. The plate measurements are relatively high due to the leakage contributions in the frame and the door of the shielded chamber.

The data was collected in a laptop, that was directly connected to the network analyzer, and processed in MATLAB. The normalized results are depicted in Figure 10. The fluctuations are mainly due to that the chamber is not anechoic, which causes a standing wave inside the chamber, and the fact that the door was not completely closed to let the cable of the receiving antenna through the chamber. The short distance between the antennas and the window affects the curve and the finite size of the window may give rise to diffraction patterns. The improvement of the soft coat window with the FSS over the same window without the FSS is roughly 10 dB in the bands of interest (900 MHz – 2 GHz). The hard coat window has a higher damping than the soft coat, especially from 1.4 GHz to 1.9 GHz. This behavior was expected because the hard coat window was manufactured to work as a single pane configuration.

There is a mismatch in the resonant frequency and the amplitude between the measured transmission and calculated transmission. That can be explained by the uncertainty in the value of the permittivity of the glass and of the finite structure in the measurements. The simulated curve is much smoother than the measured one.

# 6 Concluding remarks

Design, manufacturing, and measurements of frequency selective windows are presented in this paper. The analysis and numerical simulations are verified by measurements. The parameters of the elements present in the FSS are straightforward to design. The size of the element relates to the resonant frequency, the width of the loop relates to the percentage of removed material and the interelement spacing relates to the bandwidth.

The manufacturing of the hexagonal slits in the metallic coating of the glass suffered from several deviations from the original design. The engravings are much deeper than the actual thickness of the metallic coating, and the depth varies along the window. The soft coat window is also sensible to handling and can only be used in double glazing configurations. Nevertheless, the measurements show that there is a transmission improvement over the original window of 10 dB in the frequency band between 1 GHz and almost 2.5 GHz. The importance of the conductivity of the metallic coating was also analyzed. High conductivities provide good FSS performance, whereas materials with low conductivity degrades the spectral selectivity of the structure.

The use of FSS is highly beneficial in the energy saving windows in an indoor outdoor communication point of view. A more precise manufacturing can give even better results and make the element geometry invisible, which is a requirement for successful commercial implementation.

A general conclusion is that FSS technology seems to be an inexpensive solution to the problem of wireless communication in buildings with energy saving windows. With an increasing demand on wireless communication, simple designs like a bandstop space filter for Wireless LANs or bandpass filters like the one presented in this paper can lead to more efficient radio frequency management.

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