Thin Diffraction Grating Technology

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***Abstract*—Reflective diffraction gratings employ periodic arrays of a given three dimensional structure to produce appropriate constructive and destructive interference to redirect an incident wave. Depending upon the angle of incidence, the thickness required for this structure can range from a fraction of a wavelength to several wavelengths. Whilst such a thickness does not present a problem for optical applications it can make the diffraction grating very bulky for radio applications, notably in the lower frequency bands. This paper presents a new thin diffraction grating employing resonant structures, whose thickness is only 1/34th of a wavelength.**

***Index Terms*—Thin, Diffraction, Grating, Resonant, ILS, stealth**

I. INTRODUCTION

Reflective diffraction gratings consist of a periodically repeating three dimensional structure. They redirect incoming radiation as a function of its angle of incidence and its wavelength. They may also suppress the specular reflection encountered on planer structures. This last property can be exploited to prevent unwanted radio reflections, most notably in the field of radio navigation, where buildings can introduce interference to received signals [1,2,3].

The thickness required for conventional diffraction gratings to effectively suppress specular reflections depends upon the angle of incidence and the wavelength of the incoming radiation. For practical applications in the VHF band structures as thick as 1 m are frequently required. It is possible to build such diffraction gratings (indeed a 60cm grating has been successfully implemented on a building at Toulouse International Airport [4,5]) but their weight requires the building to possess a reinforced support structure. The striking appearance of conventional diffraction gratings also makes them unsuitable for certain non-industrial buildings.

In this paper we present a new solution to this problem: A thin reflective diffraction grating that exploits resonant structures. A theoretical development is exposed, along with the results of simulation parameter sweeps. Finally, the results of measurements performed on a full size demonstrator are presented for both dry and wet conditions.

II. THICK DIFFRACTION GRATINGS

Traditional, 'thick' diffraction gratings consist of a periodic three dimensional array of elements (Figure 1). For an incident plane wave, with a given angle of incidence, θ_{inc}, and angle of diffraction, θ_{diff}, the same feature on neighbouring periods (A and A') will produce an identical amplitude of scattered waves but the phase will be shifted due to an additional outgoing path difference for point A of $-d\sin\theta_{diff}$ and an additional incoming path difference at point A' of $d\sin\theta_{inc}$.

For constructive interference to occur, the difference of these two path contributions must be equal to an integer number, *m*, of wavelengths, λ, giving us the grating equation.

$$d\left(\sin\theta_{inc} + \sin\theta_{diff}\right) = m\lambda \quad (1)$$

We are particularly interested in applications that suppress the specular wave and concentrate the radiated energy towards the incident direction. For $\theta_{inc} = \theta_{diff}$ the grating equation reduces to the well-known Bragg condition [6].

$$d = m\lambda / 2\sin\theta_{inc} \quad (2)$$

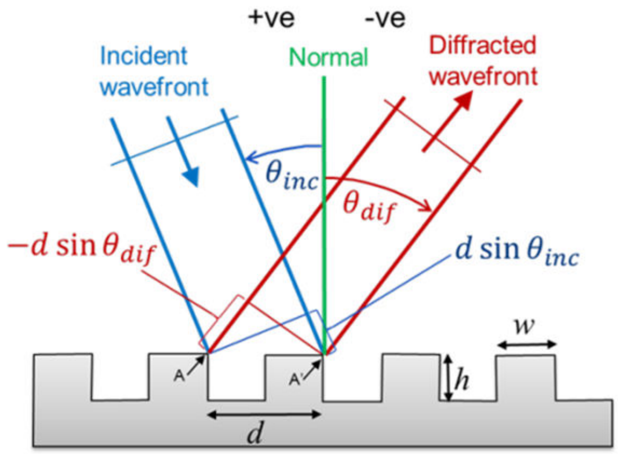

Figure 1. A conventional 'thick' diffraction grating

The grating equation tells us nothing about the amplitudes of the scattered waves. Such information must come from either specific analytical models or, more generally, from numerical simulation. In order to suppress the specular wave, the guiding principle is that one part of each period must be π radians out of *phase* with another part of the period; the two contributions possessing a similar *amplitude*. The π phase shift is usually generated by a path difference due to the varying thickness of the grating. This results in structures that vary between fractions of a wavelength to several wavelengths in thickness.

III. AN APPLICATION FOR RADIO NAVIGATION

One particularly useful application of reflective diffraction gratings in the VHF band is to prevent buildings from generating perturbations to aircraft radio navigation systems.

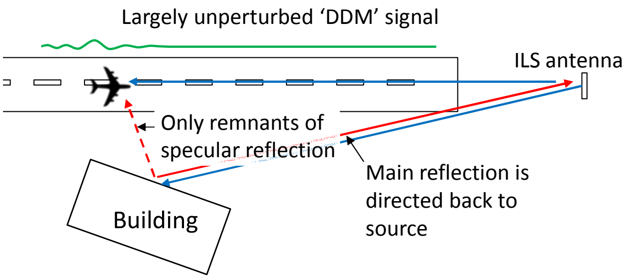

Figure 2. Diffraction grating solution for ILS interference

In Figure 2 we see the example of the Instrument Landing System (ILS). The ILS localizer guides aircraft laterally along the runway centreline in reduced visibility conditions by emitting a spatially modulated signal. The received signal can be perturbed by unwanted reflections coming from nearby obstacles such as buildings. To avoid incidents of aircraft exiting the runway, planning permission is restricted within these zones, unless it can be demonstrated to aviation authorities that the building does not produce perturbations in excess of thresholds defined by the International Civil Aviation Organisation (ICAO) [7,8].

A diffraction grating can provide just such a solution. As we see in Figure 2, a specular reflection that would have crossed the runway and perturbed incoming aircraft, can be redirected towards the emitting antenna where it poses no problem.

IV. THIN DIFFRACTION GRATINGS

The VHF frequencies employed for the ILS localizer antenna result in very deep diffraction gratings. There is a need for a thinner solution.

It is not immediately obvious how a thin diffraction grating can generate a sufficient phase shift due to a path difference. We therefore employ a different approach: We create a periodic phase difference directly in the currents induced by the incoming plane wave. This is achieved by the periodic structure displayed in Figure 3, which has been specifically designed to operate with a transverse magnetic incident field [9].

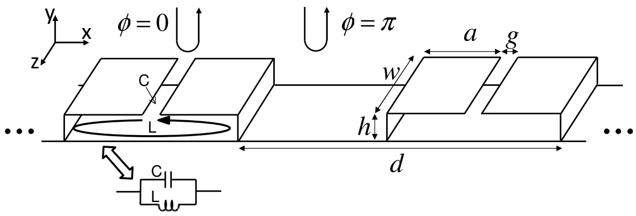

Figure 3. A first design for a thin diffraction grating

One part of the diffraction grating comprises a planar section that reflects the incoming wave in the y direction with a phase difference of π. Alternating with these sections are resonant circuits formed by folded metallic sheets to produce a rectangular tubular structure possessing a slit. The slit acts as a capacitance and the rectangular tube acts as an inductance. Together they form a parallel LC circuit. By selecting appropriate dimensions for the tube and the slit, this circuit may be designed to resonate at any selected frequency. At resonance the incoming wave is reflected without any phase shift. We may therefore obtain the desired destructive interference.

Although the first design was seen to work well in simulations, it presented a problem for outdoor applications: In practice it is necessary to employ a dielectric spacer to hold the metallic plates in place. There are several materials that can be used for this, such as expanded polystyrene foam, and in itself this poses no problem (although the permittivity of the spacer needs to be taken into account when designing the resonant circuits).

The problem arises when wind-driven rain produces a layer of water on the dielectric structure. Since water is so strongly polarizable ($\varepsilon_r \approx 90$ within the VHF band [10]) its presence can change the capacitance of the gap capacitor, and de-tune the resonant circuit. This can occur even if the rain layer is galvanically isolated from the circuit.

In order to minimize this effect, a second design was explored (see Figure 4) [11]. Now the only capacitance is that between the plate A and the plane B (this capacitance was already present in the first design but it did not dominate). The advantage of doing so is that this capacitance is generated within a zone that is screened from any external water layer by the plate A. It is still necessary to keep the rain layer at a further distance of approximately 8 cm, but this can be achieved easily with a dielectric screen.

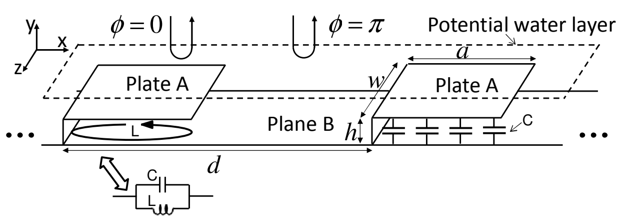

Figure 4. A second design for a thin diffraction grating

V. THEORETICAL DEVELOPMENT

In order to find approximate dimensions for the resonant circuit we follow a development similar to that presented for high impedance surfaces in [12]. We emphasise that this reasoning acts only as a guide, and that the fact that neither the plane B nor the resonant structure uniformly cover the plane implies that the concept of equivalent surface impedance is not strictly valid.

The phase change, ϕ, of the wave reflected by the resonant structure is

$$\phi = \mathrm{Im}\left\{\ln\left(\frac{Z-\eta}{Z+\eta}\right)\right\} \tag{3}$$

where η is the impedance of free space, and Z is the impedance of the LC circuit (of inductance L, capacitance C, at an angular frequency of ω)

$$Z = \frac{i}{1-LC\omega^2} \tag{4}$$

We can see from the previous two equations that the zero phase condition is satisfied at the circuit resonant frequency, ω_0.

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{5}$$

In the first design (dimensions as in Figure 3) the capacitance is approximated by that of coplanar sheets

$$C_{d1} = \frac{2w\varepsilon}{\pi}\operatorname{arccosh}\left(\frac{a}{g}\right) \tag{6}$$

where ε is the permittivity of the surrounding medium.

And in the second design (dimensions as in Figure 4), the capacitance is very roughly approximated as that of a parallel plate capacitance

$$C_{d2} = \frac{\varepsilon wa}{h} \tag{7}$$

In both cases the inductance is that of the enclosed loop

$$L = \frac{\mu ah}{w} \tag{8}$$

where μ is the permeability of the surrounding medium.

We fix as a design goal h = 8 cm, since expanded foam panels are readily available in this thickness. As expected, the resonant frequency is independent of *w*, and values of 10s of cms are sufficient to generate resonances in the desired VHF band.

VI. GRATING DESIGN

In practice the resonant circuits and the gaps are strongly coupled, so in order to find optimal dimensions it is necessary use numerical simulations. The time domain solver of CST

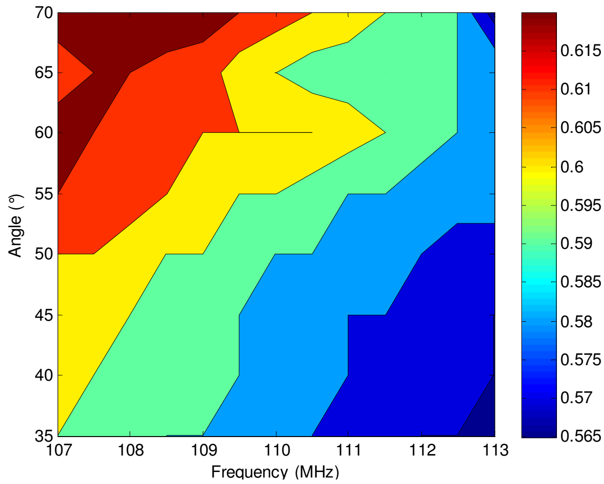

Figure 5. Optimal values of the plate width, a (m).

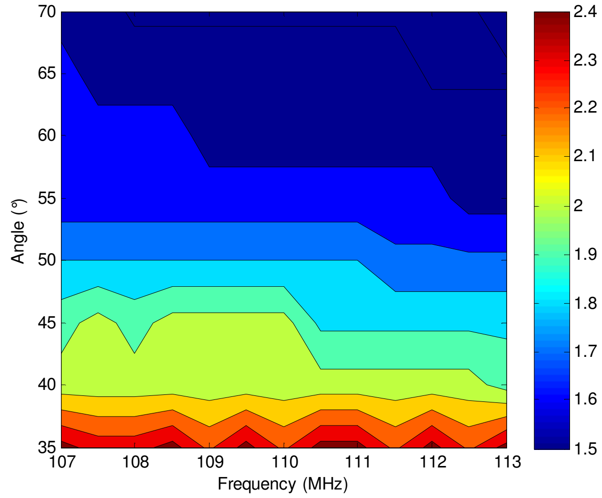

Figure 6. Optimal values of the period, d (m).

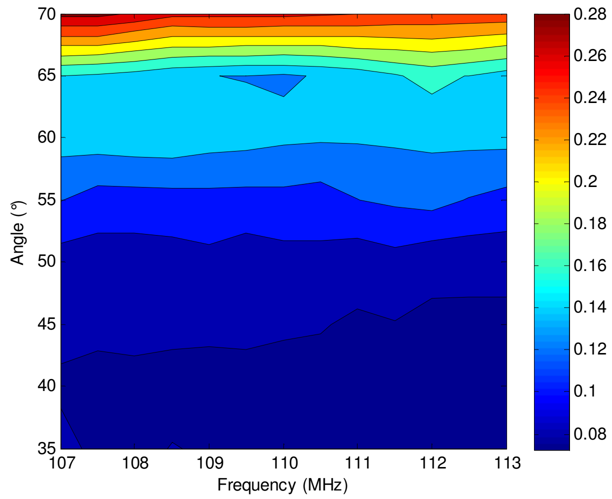

Figure 7. The simulated signal reduction (relative to bare plate) corresponding to the above optimal dimensions.

Microwave Studio was used. A sample panel measuring 30m by 5m was simulated for angles of incidence ranging from 35° to 70° over a range of frequencies (107-113 MHz) encompassing the ILS band (108-112 MHz). The goal function was the reduction of the specular reflection. The optimum values for the plate width, *a*, and the periodicity, *d*, are displayed in Figure 5 and Figure 6. As expected, *a* is dominated by the required resonant frequency and *d* very approximately follows Bragg's law. Figure 7 displays the resulting simulated signal reduction, corresponding to the optimal dimensions shown in Figure 5 and Figure 6.

VII. FIELD TRIALS

In order to test the technology in a realistic setting, we built a full scale mock-up of a building façade. It is not a trivial matter to perform scattering measurements in the VHF band on such a large structure. To do so we decided to adapt an existing installation of an ILS localizer antenna.

Originally, we intended to implement a movable test platform that could be rotated to produce any selected angle of incidence. One idea was to use a structure mounted upon a lorry trailer. However, preliminary calculations indicated that the structure needed to be 30 m in width and 5 m in height to produce sufficiently sensitive measurements. For these dimensions, only a fixed structure could be implemented at a reasonable cost. We therefore chose to orient the panel at an angle of incidence that corresponds to an identified real world airport application; 53°.

The panel was built upon a hill at the aerodrome of Cahors. The layout of the test is displayed in Figure 8. A permanent ILS localizer antenna is situated at 297 m beyond the end of the runway. A test vehicle measured the reflected field, following a trajectory along the runway centreline.

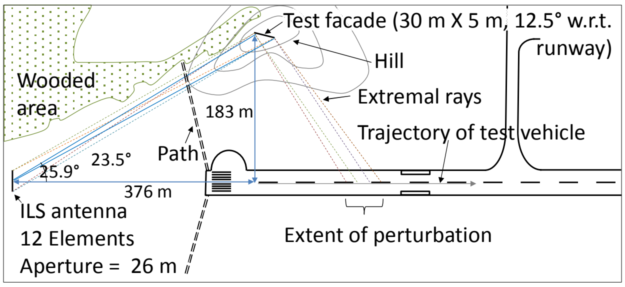

Figure 8. The layout of the test.

Ordinarily the ILS antenna possesses the radiation pattern displayed by the blue curve in Figure 9. The panel subtends an angle between 23.5° and 25.9° with respect to broadside, placing it at a very weakly illuminated position. For this reason the antenna excitation was modified by an appropriate placement of attenuators and phase shifters to produce the radiation pattern displayed by the red curve in Figure 9. Note that the null is preserved at 0° which is the position of the test vehicle along the runway axis. The measurements in Figure 9 were performed along the double-dashed line in Figure 8.

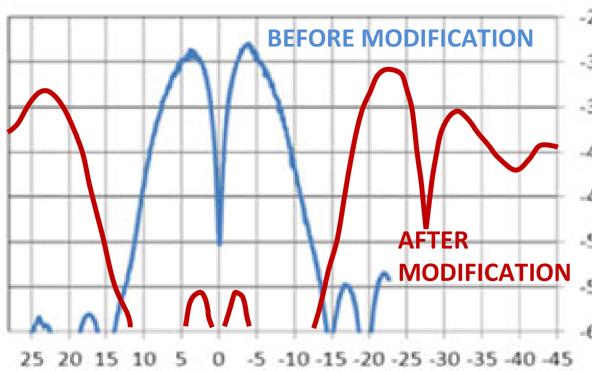

Figure 9. Measured radiation pattern of ILS localizer antenna before and after modification

The final form of the panel is displayed in Figure 11. Note that the panel is held in place by scaffolding, anchored with 10 metric tons of concrete blocks. The protective screen possesses the distinctive regulatory colours of vertical red and white stripes, as well as night time lighting to make it visible to the other users of the aerodrome.

Numerous measurements were performed. The black curve of Figure 12 shows the measured perturbations before the screen was built. The small observable oscillations are due to reflections from the surrounding environment. The red curve displays the measured perturbation once the conventional planar panel was built. The panel consisted of steel sheets with a vertical corrugations 5 cm in depth, in order to be representative of a real industrial building. We observe a significant perturbation of 262 µA peak to peak, allowing even a strongly attenuated reflection to be visible above the noise floor.

Once the thin diffraction grating was installed the perturbation was reduced by **91%**, (green curve). We also wanted to test the behaviour of the diffraction grating when subjected to wind-driven rain. These conditions were simulated thanks to the local fire-brigade who directed three jets of water towards the screen producing an irregular water layer of approximately 2 mm in thickness. The resulting perturbations (blue curve in Figure 12) are almost the same as those obtained in dry conditions.

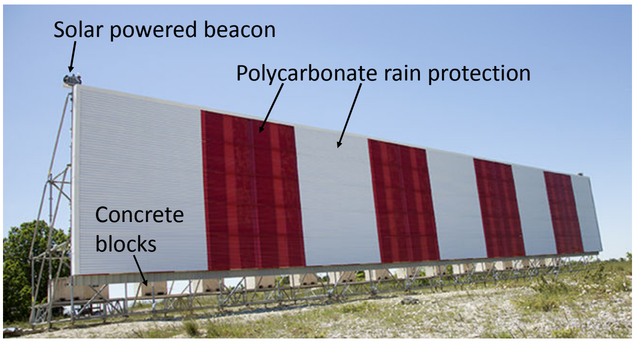

Figure 11. The thin diffraction grating behind its protective screen

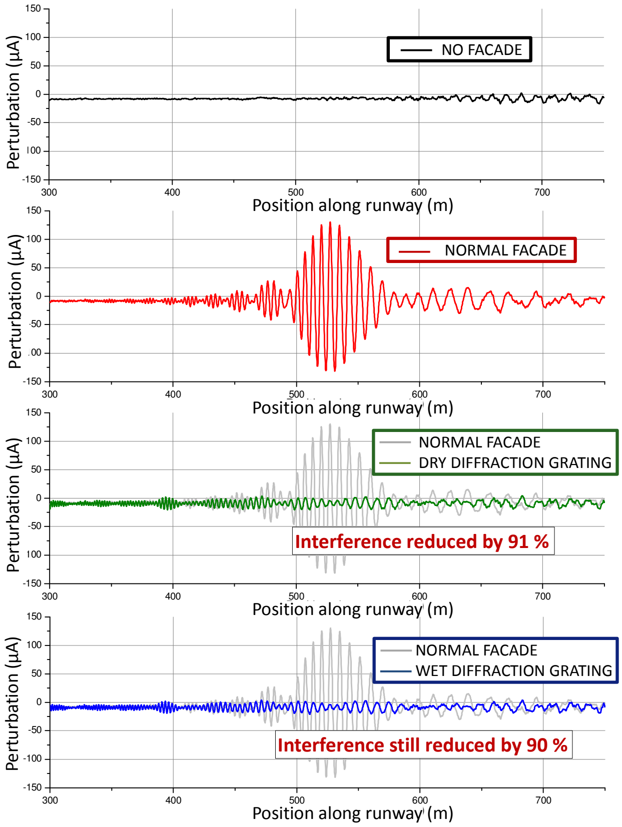

Figure 12. The measurement results

It would have been desirable to also measure the retro-reflected signal to characterise whether absorption is also taking place on the panel. Unfortunately, this is not possible with our setup as measurements can only be performed on the runway axis along the null of the radiation pattern. There are however very few loss mechanisms at VHF frequencies in our structure (finite aluminium conductivity, loss in expanded polystyrene spacer and polycarbonate rain protection) and simulations showed no substantial differences when lossy or lossless materials were employed.

Measurements were also performed for other frequencies within the ILS band. The resulting fractional reduction of the specular reflection is displayed in Figure 13. We note that the solution is relatively broadband compared to the allowed ILS frequencies. We observe a good agreement obtained with our simulations used in the design of the panel (red curve in Figure 13).

In conclusion, the measurements validated the proposed idea of an electromagnetically thin diffraction grating, producing an observed signal reduction of 90% that is more than sufficient for almost all air navigation applications.

On a practical basis, the field trial also demonstrated that the diffraction grating could easily be installed on a standard hangar façade. The technology is now commercialized by Airbus.

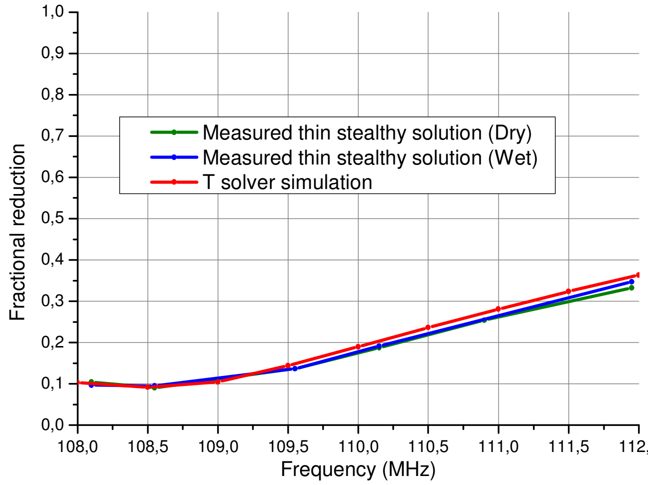

Figure 13. Measured signal reduction over the ILS bandwidth

ACKNOWLEDGMENT

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