Phase Hologram Composed of Square Patches on a Thin Dielectric Sheet

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1. Introduction

At microwave, millimetre-wave and submillimetre-wave frequencies, holographic principles can be applied for different antenna applications, including low profile antenna designs [1,2], compact antenna test ranges (CATR) [3] and, by extension, Fresnel zone plates (FZP) [4]. These low-cost antennas, designed from binary computer-generated amplitude holograms, are easily manufactured using conventional etching processes. However, amplitude holograms suffer from poor aperture efficiency, which makes them impractical for many applications.

On the other hand, it has been shown that the efficiency of phase holograms is far superior to that of amplitude holograms [5]. However, at microwave, millimetre-wave and submillimetre-wave frequencies, phase holograms require machining, which is an expensive and time-consuming process when compared to a conventional etching process.

In [6], it has been shown that it is possible to obtain the behaviour of a phase hologram at microwave frequencies through a volume hologram approach by cascading several layers of dielectric sheets on which metallic implants are etched. However, the significant number of layers required limits the practicality of this concept.

In this paper, a means of generating a transmission phase hologram using a thin flat dielectric sheet is studied. The goal was to determine the amount of phase shift achievable for a single dielectric sheet while maintaining a low level of insertion loss through the structure. Ideally, a phase shift of up to 360° is desirable, although some applications may require less [7].

This paper focuses on the phase variation obtained by etching subwavelength square metallic patches of varying size on a dielectric sheet. In this preliminary work, both single-sided and double-sided etched sheets were investigated. The maximum size of the square metallic patches was kept to a fraction of a wavelength in order to decrease the quantization error resulting from the discretization of the ideal phase profile using the computer-generated hologram technique. The resultant simple structure is an attractive candidate for practical antenna designs at microwave and millimetre-waves.

2. Unit Cell Design

The unit cell used for the thin phase hologram study is presented in Fig. 1a. It consists of a square metallic patch of size \(a\) etched at the centre of the unit cell of size \(s\). The metallic patch (in black) is etched on a dielectric sheet (in grey) having a thickness \(h\) and a relative permittivity \(\varepsilon_r\). The unit cell with proper boundary conditions is used in a commercial electromagnetic simulation package to mimic an infinite uniform periodic structure, similar to the one shown in Fig. 1b. The simulation package used is Empire™ XCcel by IMST [8], which uses the finite-difference time domain (FDTD) technique. In Empire™ XCcel, perfect electric conductor / perfect magnetic conductor (PEC/LMC) boundary conditions are placed as shown in Fig. 1b in order to excite the structure with normal incidence using vertical polarisation of the electric field. This way, an infinite periodic structure is well approximated for the electrically small cell sizes being considered.
3. Simulations

The following subsections describe different simulations and analyses at 30 GHz for a sample having a relative permittivity of $\varepsilon_r = 2.2$, a thickness of $h = 1$ mm and a unit cell size of $s = 1$ mm. The unit cell size corresponds to a tenth of a wavelength, which would lead to a low quantization error.

3.1 Layers of patches

Metallic patches were first simulated on a single layer of the dielectric sheet and then on both the front and back layers. The transmission results are presented in Fig. 2. In Fig. 2a, it is seen that varying the patch size $a$ while keeping all other parameters constant results in a change in transmission phase. This is a basic requirement for realizing a phase hologram using conventional etching while keeping the thickness of the dielectric sheet constant. However, this phase change is also accompanied by an insertion loss (see Fig. 2b), which is undesired. This insertion loss should be kept as low as possible, since high insertion loss leads to poor transmission and consequently low efficiency.

From Fig. 2c, it is seen that etching patches on both faces of the dielectric sheet significantly improves the phase shifting performance. For an insertion loss below 3 dB, the single layer phase shift range is about 30°; for the double layer, it is better than 135°.

3.2 Unit cell size

Two cases of unit cell size, i.e. $s = 1$ mm (one tenth of a wavelength) and $s = 2$ mm (one fifth of a wavelength), were simulated to determine the effect of this parameter on the phase variation. From Fig. 3, it is found that the smallest $s$ results in a more abrupt variation in the region where the value of $a$ approaches that of $s$. Overall, for a given phase variation, the same insertion loss is observed in both cases (see Fig. 3c), however they do not happen for the same ratio of $a/s$. For manufacturing purposes, a larger $s$ should require less etching accuracy; however it is more subject to quantization error.

3.3 Relative permittivity and thickness

The thickness and relative permittivity of a dielectric sheet are crucial parameters that need to be selected carefully. In some cases, the insertion loss will remain low for a large range of patch size while an optimum phase shift is obtained; in some other cases, the insertion loss will be high for very small values of patch size, therefore leading to a non-practical situation. Surface plots of the amplitude and phase in the thickness versus relative permittivity domain, like the ones shown in Fig. 4 and 5, may be helpful to choose these parameters.

In addition, curves of the equivalent thickness and equivalent relative permittivity with variable patch size $a$ for the double layer case with $s = 1$ mm are overlaid in Fig. 4 and 5. These curves were obtained by mapping the transmission phase and insertion loss for each patch size $a$ onto the corresponding points of the surface plots in Fig 4 and 5. Fig 4 shows that a low relative permittivity is preferred since a high relative permittivity results in high insertion loss. Fig. 5 shows that a thicker substrate results in a faster phase variation. However, very thick samples are not recommended because of their size, weight and cost. Consequently, a compromise must be reached.
4. Limitations

One of the main challenges appears to be the tolerance and sensitivity of the etching process for $a/s$ close to unity. In this region, the insertion loss and phase shift vary significantly for only small variations of $a$. This means the etching process has to be well controlled in order to avoid errors resulting from overetching or underetching.

Another limitation is the achievable phase variation for reasonable insertion loss. In the actual case, the phase range is better than 135° for less than 3 dB of insertion loss; however the rapid phase variation for large ratios of $a/s$ may reduce the practical phase range.
5. Discussion and Future Work

Although a 360° phase variation was not achieved with a single sheet, the 135° phase range achieved to date will allow for improvements of conventional amplitude hologram structures. The presented phase hologram approach could be used in conjunction with a conventional amplitude hologram to form some kind of mixed hologram. More specifically, it is expected that this could easily lead to the improvement of FZPs.

Since the phase variation is limited for single and double layer cases, one method to extend the phase range may be to add a few extra layers of metallic patches. Having two layers on a single dielectric sheet is very practical as it requires no bonding. However, having to bond 2 or 3 dielectric sheets in order to obtain respectively 3 or 4 layers of metallic patches is not much more difficult in terms of fabrication despite some increase in cost.

6. Conclusions

The fundamentals for the realization of practical thin transmission phase holograms were demonstrated from simulations. For a 1 mm thick sample of relative permittivity of 2.2, a phase variation better than 135° was obtained. Such a phase variation could lead to the improvement of some actual structures. Additional results, including experimental measurements, will be presented at the conference.

References