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Fano Resonance Based Multiple Angle Retrodirective Metasurface

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Abstract—In this paper, a Fano resonance based multi-angle retrodirective metasurface is introduced. The aim is to investigate the potential of Fano-resonating structures, to suppress the losses and complexity of metasurface designs with high super-cell periodicities. A dolmen structure is given in this case which is well known for its Fano-resonating characteristics. It consists of two sub-radiant modes and one super-radiant mode. The design is given following the generalized phase law of reflection and surface impedance modulation for higher efficiency. The super-cell design has been given with a periodicity of 5.74λ , and frequency of 24 GHz. This is to achieve numerous retro-reflections at different incident angles based on Floquet harmonic analysis. When the sub-radiant mode is excited, retrodirectivity has been achieved at 17 angles of incidence. On the other hand, by exciting the super-radiant mode, retrodirectivity has been achieved at three incident angles due to the coupling between the individual elements of the Fano-resonating structure. The monostatic RCS has been calculated to determine the performance of the retrodirective metasurface.

Index Terms—Fano resonance, retrodirectivity, multiple angles, generalized phase law, surface impedance modulation, Radar cross section enhancement.

I. INTRODUCTION

Metasurfaces [1] have gained lot of popularity in terms of wave control and manipulation for different applications [2]–[4]. Anomalous reflection has been proved to be achievable following the generalized phase law of reflection [5], that is, by introducing a phase gradient between scatterers, a metasurface can be designed to control an electromagnetic wave in a desired direction. Particularly for retro-reflection for a range of incident angles, this phenomenon has been in previous work [6], using the superposition of different designed super cells for different angles of incidence. It has also been reported by V.S. Asadchy et al [7], that with proper engineered surface impedance for a super-cell design periodicity which is greater than λ according to Floquet harmonic analysis a multi-channel retro-reflective metasurface can be achieved [8].

However, with the increase of periodicity of up to 5.74λ , the engineering of the surface impedance can become complex and the structure becomes very lossy. Sub-radiant resonances are well known to suppress radiation losses and overcome broad spectral responses. The interaction between the sub-radiant modes and the super radiant mode is known as Fano-resonance [9], [10], which results in a narrow spectral structure giving rise to a highly sensitive device at a selective

frequency [11], [12]. These structures can be good candidates for applications such as nano sensing [13], imaging and highly sensitive devices [14].

In this paper we investigate the potential of Fano-resonating structures in order to suppress the losses in metasurfaces with high super-cell periodicities and to decrease the complexity of the optimization process to achieve multi-angle retrodirective metasurfaces using one super-cell design. A dolmen structure is introduced for its Fano-resonance properties [9]. The sub-radiant modes are tuned with a phase gradient following the generalized phase law of reflection with a fixed super-radiant mode. The coupling between the resonating structures of the dolmen unit cell, can give rise also to retro-reflection at some angles of incidence when the super-radiant mode is excited. A super-cell design of periodicity 5.74λ is chosen to achieve retro-reflection for a numerous number of incident angles, since with respect to Floquet harmonic analysis [15], with an increase of periodicity greater than λ more channels are present. In terms of application prospects, the multi-angle retrodirective metasurface can be a good candidate for highly sensitive radar systems [16] to increase the RCS of targets where backscattering is poor.

II. PRINCIPLE OF OPERATION AND DESIGN METHDOLOGY

In this work, we use dolmen fano-resonating structures, which are based on spectrum engineering for highly sensitive devices, and introducing a phase gradient by tuning the sub-radiant modes following the generalized phase law of reflection, particularly for retro-reflection, while fixing the super-radiant mode. The unit cell structure is shown in Fig. 1.

The dimensions of the dolmen unit cell are given as follows: the two sub-radiant modes are of same dimensions in the x-direction, $L_1 = 6.5 \text{ mm}$ and $W_1 = 1 \text{ mm}$. Whereas, for the super-radiant mode in the y-direction, $L_2 = 2 \text{ mm}$ and $W_2 = 1 \text{ mm}$, with a gap $g = 1 \text{ mm}$ between the sub-radiant modes and the super-radiant modes.

The periodicity of the super-cell design, is determined following the integration of the generalized phase law of reflection [5] from 0 to 2π . The periodicity L_x of the super cell design is given by:

$$L_x = \frac{\lambda}{2 \sin \theta}, \quad (1)$$

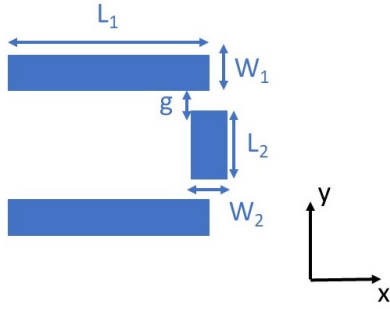


Fig. 1. Unit cell dolmen structure of 3 elements, two sub-radiant modes in the x-direction of dimensions L_1 and W_1 , and one super-radiant mode in the y-direction of dimensions L_2 and W_2 . With a gap g between the two sub-radiant modes and the super-radiant mode.

where the λ is the wavelength and θ the angle of incidence. In our case, θ is chosen at 5° for a frequency of 24 GHz, thus L_x is equal to 5.74λ . According to Floquet Bloch analysis [15] for a metasurface design of periodicity larger than λ , a high number of open channels can exist where retrodirectivity can be achieved in addition to choosing the desired angle. For a periodicity of 5.74λ , the design becomes very lossy and complex in terms of optimization. The usage of a Fano-resonance structure can be a good candidate to suppress the losses for super-cells with high periodicities. The super-cell is divided into 8 unit cells, where the dimensions of the sub-radiant modes L_1 are both tuned similarly in the x-direction. The phase gradient $\phi = 2\pi/8 = 45^\circ$. The dimensions of the sub-radiant modes are determined following the phase of the reflection coefficient which is shown in Fig. 2.

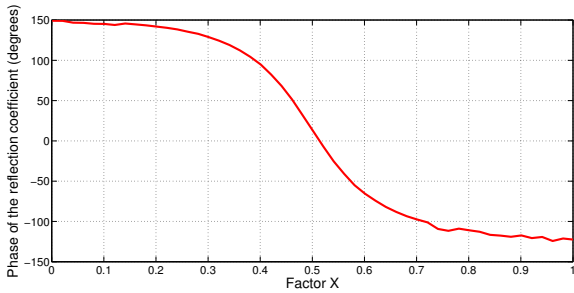


Fig. 2. Phase of the reflection coefficient with respect to that of Factor X which is multiplied with the dimensions of the sub-radiant modes at 24 GHz.

The tuned dimensions are given as $L_{1(initial)} \times \text{Factor X}$ with $L_{1(initial)} = 6.5\text{mm}$, which is determined in Fig.2 with respect to a phase gradient 45° . The Factors X and the dimensions of the tuned cells are given in Table 1.

In order to achieve high efficient retro-reflection at the open channels, the surface impedance should be properly engineered and optimized to be purely reactive, as given in the following equation:

$$Z_s = j \frac{Z_{TM}}{\tan(\frac{\phi_i}{2})} \quad (2)$$

TABLE I
DIMENSIONS OF THE SUB-RADIANT MODES L_1 (MM) TUNED WITH A PHASE GRADIENT EQUAL TO 45° FOLLOWING THE PHASE OF THE REFLECTION COEFFICIENT IN FIG. 2, WHERE THE DIMENSIONS $L_{1(initial)} = 6.5$ MM ARE MULTIPLIED BY FACTOR X TO FORM A GRADIENT METASURFACE.

ϕ_i°	Factor X	L_1 (mm)
-122.4	1	6.5
-77.4	0.6	3.9
-32.4	0.55	3.575
12.6	0.5	3.25
57.6	0.44	2.86
102.6	0.37	2.405
147.6	0.1	0.65
-167.4	1	6.5

where Z_s is the surface impedance and Z_{TM} is the impedance of air and ϕ_i is the phase of the reflection coefficient. The initial surface impedance of the dimensions given in Table 1 was calculated to be $Z_s = 15 - j326$ using Floquet boundary conditions for one super-cell design. The surface impedance has been optimized by tuning the initial dimensions to achieve a purely reactive surface impedance determined as $Z_s = 1 - j133$ where the resistance is almost tuned to zero. The optimized dimensions are given in Table 2.

TABLE II
OPTIMIZED AND INITIAL DIMENSIONS OF THE SUB-RADIANT MODES L_1 FOLLOWING THE SURFACE IMPEDANCE OPTIMIZATION AND MODULATION TO A PURE IMAGINARY VALUE.

Initial Dimensions L_1 (mm)	Optimized Dimensions L_1 (mm)
6.5	6.5
3.9	4.095
3.575	3.705
3.25	3.38
2.86	3.055
2.405	3.9
0.65	1.3
6.5	6.5

A metasurface of 4×3 super-cells of dimensions $25\text{ mm} \times 215\text{ mm}$ is designed using the optimized dimensions given in Table 2. The dolmen structures are printed on top of a grounded substrate of permittivity $\epsilon_r = 2.2$ and thickness 1.6 mm operating at 24 GHz. The metasurface is shown in Fig 3.



Fig. 3. Metasurface design using the optimized dimensions of 4×3 super-cells, of dimensions $25\text{ mm} \times 215\text{ mm}$, with a ground plane and substrate of permittivity $\epsilon_r = 2.2$ and thickness 1.6 mm.

The metasurface has been excited with a plane wave with the electric field in the X-direction of the sub-radiant modes, at a range of incident angles from -70° to 70° . The monostatic RCS has been calculated to determine the performance of the metasurface Fano-resonance based design. The monostatic RCS of the metasurface has been compared to that of a

flat metallic plate with similar dimensions to highlight the efficiency of the metasurface for retrodirectivity. The result is shown in Fig.4.

The result shows high level of retrodirectivity for almost 17 different incident angles ($-60^\circ, -52^\circ, -44^\circ, -38^\circ, -32^\circ, -21^\circ, -18^\circ, -10^\circ, -5^\circ$, normal incidence, $+5^\circ, +18^\circ, +21^\circ, +25^\circ, +32^\circ, +44^\circ, +52^\circ$) which is due to the high periodicity of the super-cell design and high sensitivity of the designed Fano-resonant dolmen structure for high efficiency and accuracy.

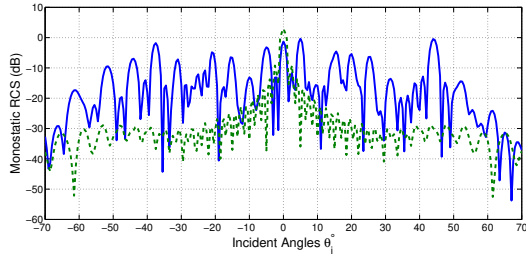


Fig. 4. Monostatic RCS (dB) of the metasurface design in blue compared to a flat metallic plate of similar dimensions in dotted green, when the electric field of plane wave is in the direction of the sub-radiant modes (x-direction) at 24 GHz .

The metasurface has also been excited with a plane wave with the electric field in the direction of the fixed super-radiant mode in the y-direction. The monostatic RCS has been calculated and compared to that of a metallic flat plate.

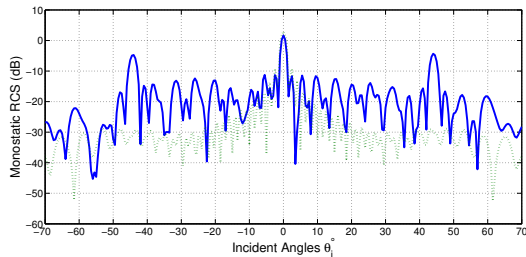


Fig. 5. Monostatic RCS (dB) of the metasurface design in blue compared to a flat metallic plate of similar dimensions in dotted green, when the electric field of plane wave is in the direction of the super-radiant mode (y-direction) at 24 GHz .

The result shows a high level of retro-reflection at three angles of incidence -44° , normal incidence and 44° compared to that of a flat plate of similar dimensions. This is due to the coupling present between the sub-radiant modes and the super-radiant mode, giving rise to retro-reflection for different angles with independent polarization for specific angles of incidence.

III. CONCLUSION

In this paper a retrodirective metasurface with high periodicity super-cell design, operating for multiple incident angles based on Fano-resonance has been introduced. The Fano-resonant metasurface design, has shown high sensitivity and

efficiency for multiple angles at the desired frequency. The concept was to suppress the losses and complexity of the design at high periodic super-cell design. The metasurface has shown to perform efficient retro-reflection for 17 angles on incidence simultaneously. On the other hand, when exciting the super-radiant mode, due to the coupling between the resonant structures of the sub-radiant modes and super-radiant mode, the metasurface has shown to perform retrodirectivity at three angles simultaneously giving rise to independent polarization metasurface design. In terms of application prospects, the Fano-resonant metasurface design can be a good candidate for highly sensitive radar systems for increasing the RCS of targets with poor backscattering.

In future work, breaking the symmetry of the sub-radiant modes can be interesting to investigate, in order to achieve multiple Fano-resonances. A prototype will be realised and the measurement results will be presented at the conference.

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