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Low-Profile Frequency Selective Surface Based Device and Methods of Making the Same

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Behdad

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(54) LOW-PROFILE FREQUENCY SELECTIVE SURFACE BASED DEVICE AND METHODS OF MAKING THE SAME

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H01Q 15/02 (2006.01)

(52) **U.S. Cl.** **343/909**; 343/770; 333/202

(58) **Field of Classification Search** 343/770, 343/895, 909; 333/134, 202

See application file for complete search history.

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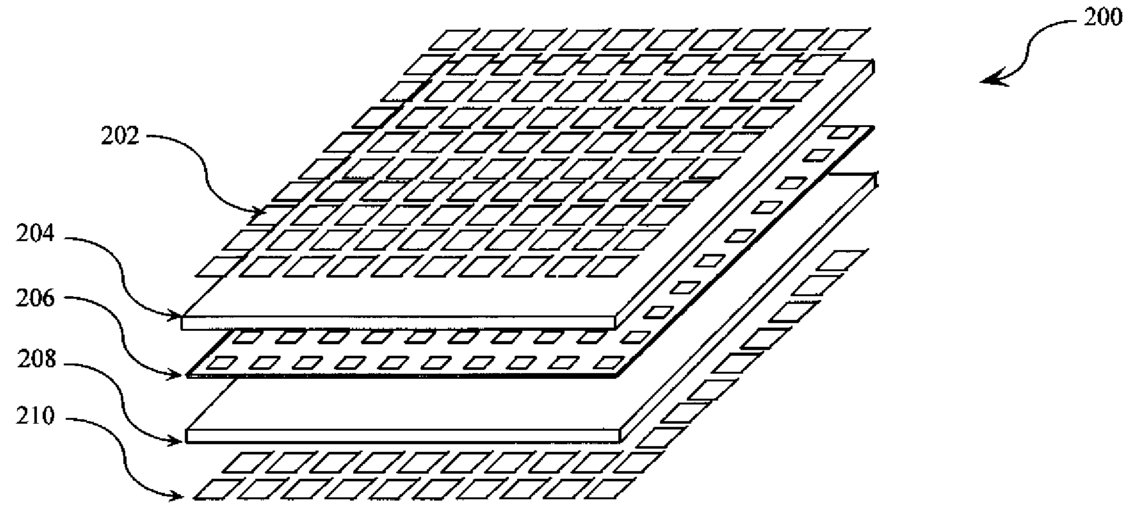
Primary Examiner—Tan Ho

(74) *Attorney, Agent, or Firm*—Patents on Demand, P.A.; Neil R. Jetter

(57) ABSTRACT

A frequency selective surface-based (FSS-based) device (**200**) for processing electromagnetic waves providing at least a third-order response. The FSS-based device includes a first FSS (**202**), a second FSS (**210**), and a high quality factor (Q) FSS (**206**) interposed between the first and second FSSs. A first dielectric layer (**204**) and a second dielectric layer (**208**) separate the respective FSS layers. The first and second FSSs have first and second primary resonant frequencies, respectively. The high Q FSS has a lower primary resonant frequency relative to the first and second primary resonant frequencies. The overall electrical thickness of the FSS device can be <λ/10. The high Q FSS has a loaded quality factor of at least thirty at the lower primary resonant frequency.

19 Claims, 12 Drawing Sheets



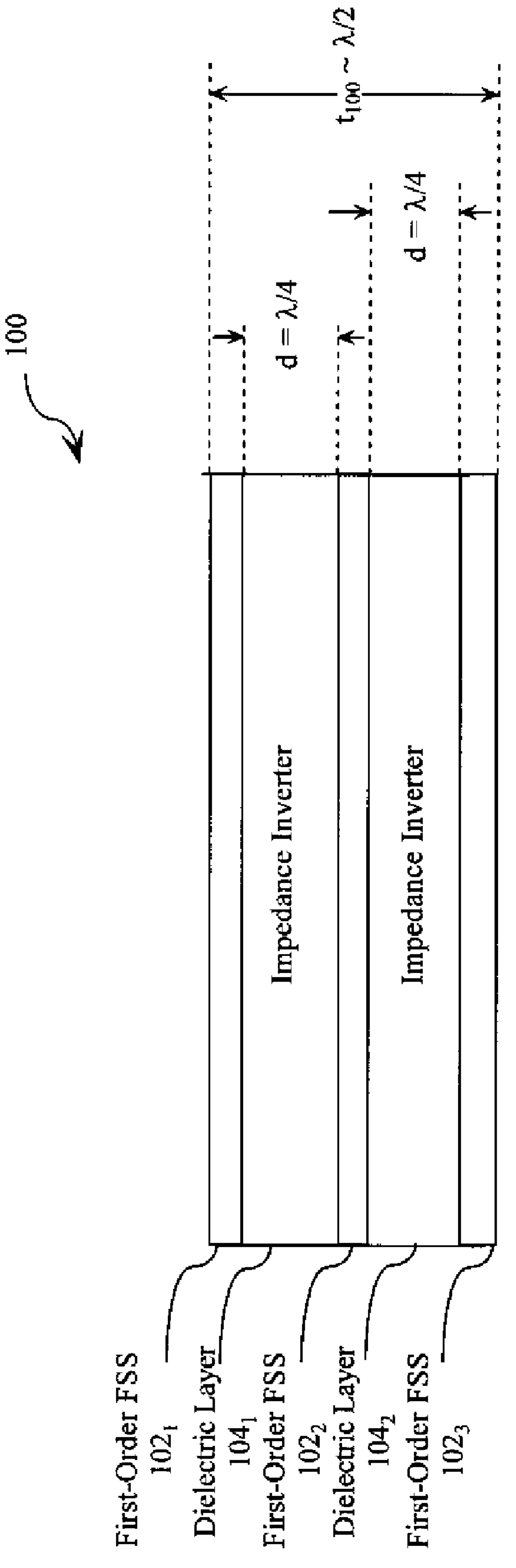


FIG. 1
(Prior Art)

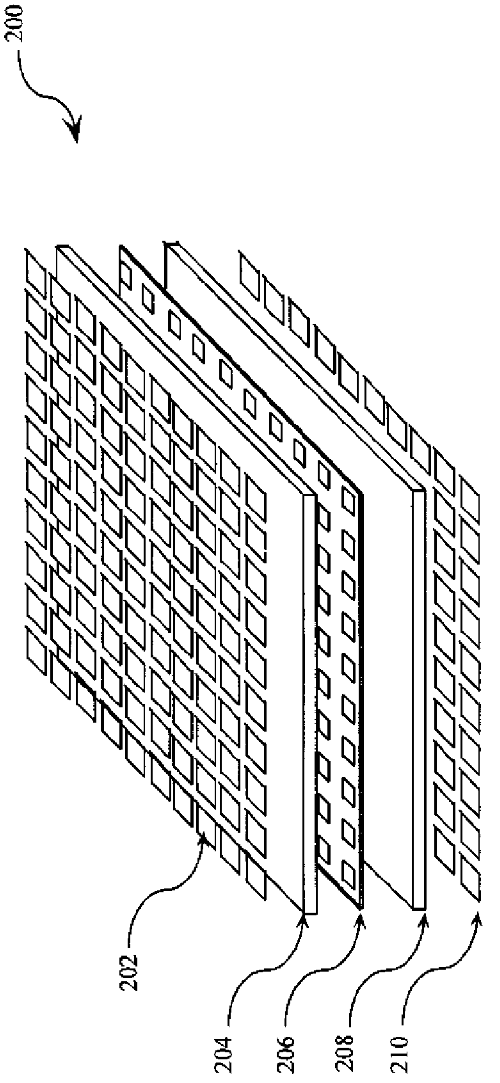

200
202
204
206
208
210

FIG. 2

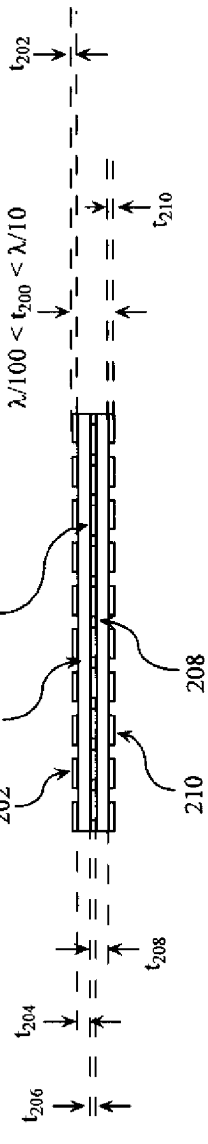

t_{202}
t_{210}
$\lambda/100 < t_{200} < \lambda/10$
206
204
202
208
210
t_{208}
t_{204}
t_{206}

FIG. 3

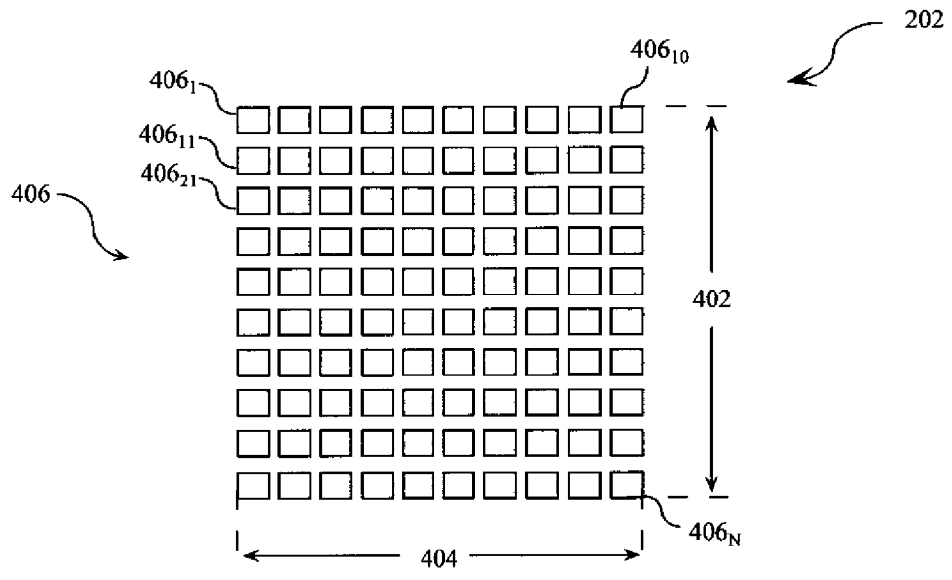

202
406_1
406_{10}
406_{11}
406_{21}
406
402
406_N
404

FIG. 4

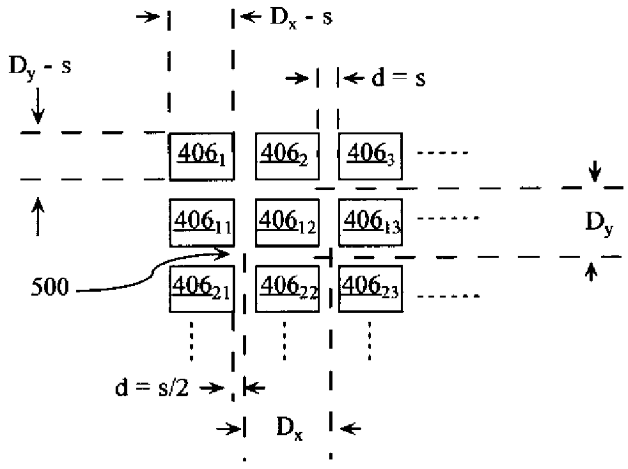

D_x - s
D_y - s
d = s
406_1
406_2
406_3
406_{11}
406_{12}
406_{13}
D_y
500
406_{21}
406_{22}
406_{23}
d = s/2
D_x

FIG. 5

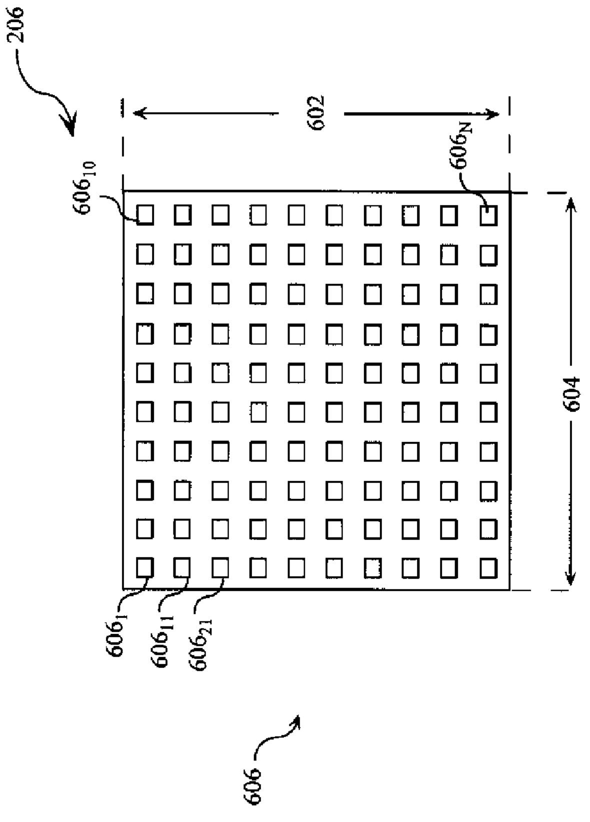


FIG. 6

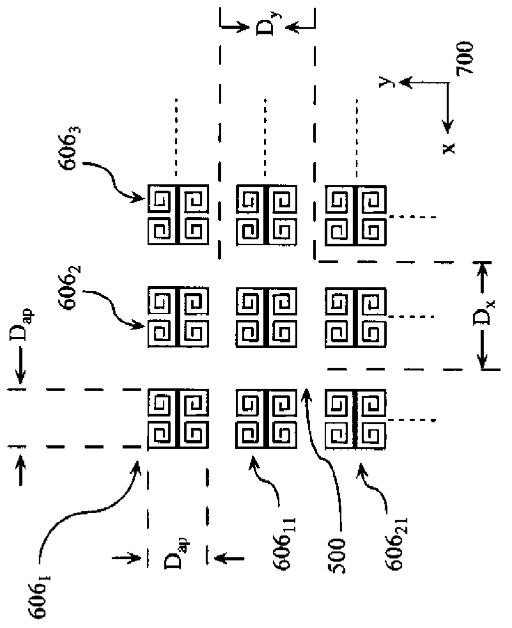


FIG. 7

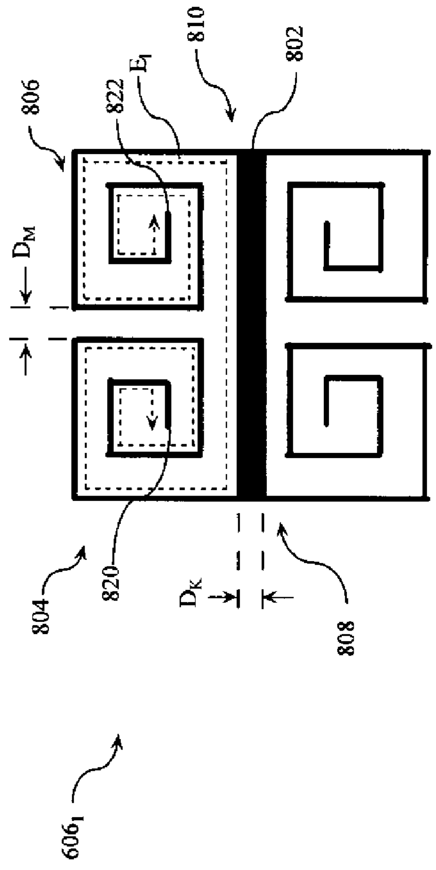


FIG. 8

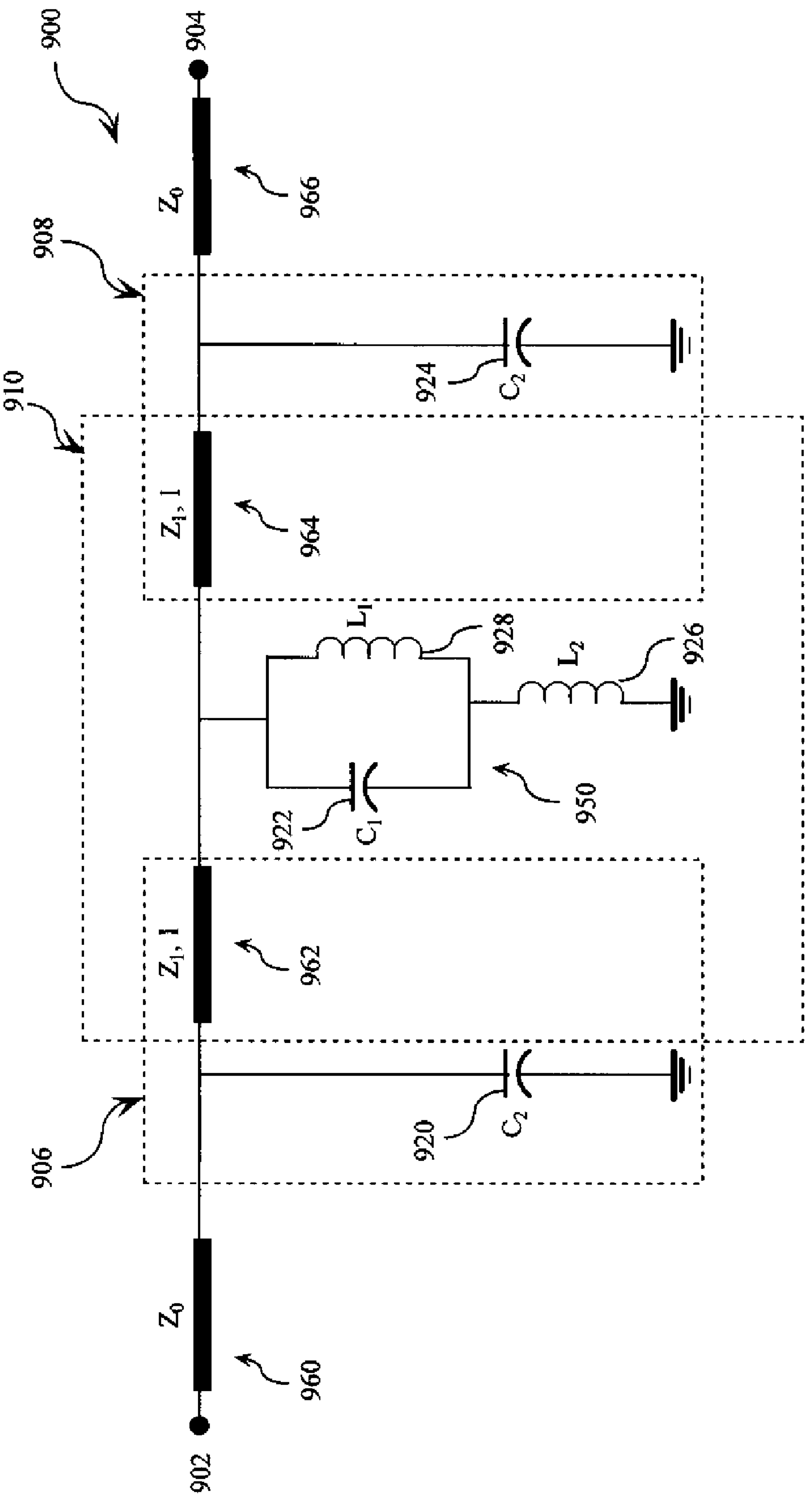

900
904
966
Z_0
908
924
C_2
910
Z_1, l
964
L_1
928
L_2
926
950
922
C_1
Z_1, l
962
906
920
C_2
Z_0
960
902

FIG. 9A

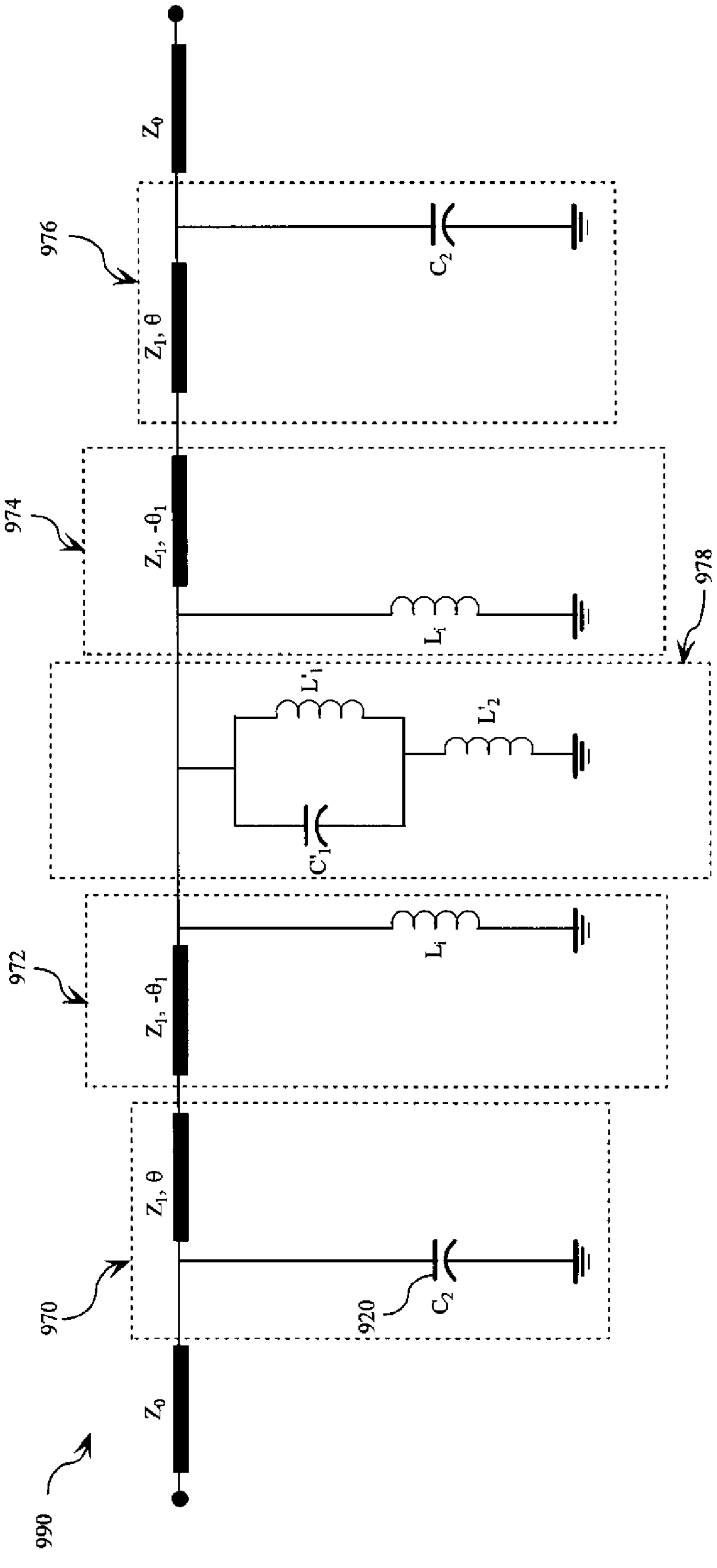

990
Z_0
970
920
C_2
Z_1, θ
972
$Z_1, -\theta_1$
L_1
978
C'_1
L'_1
L'_2
974
$Z_1, -\theta_1$
L_1
976
Z_1, θ
C_2
Z_0

FIG. 9B

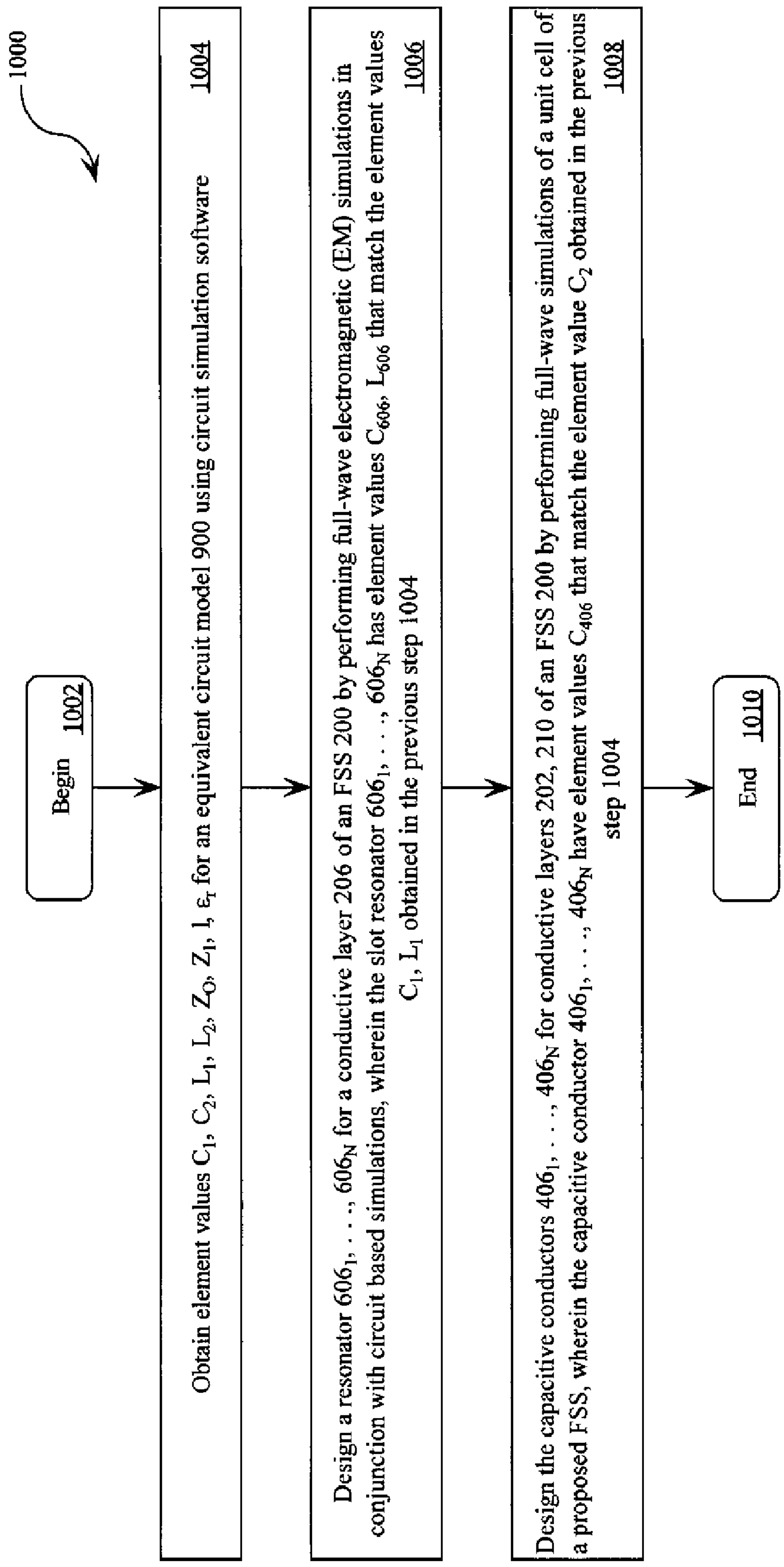

1000
Begin 1002
Obtain element values C_1, C_2, L_1, L_2, Z_O, Z_1, l, ε_r for an equivalent circuit model 900 using circuit simulation software 1004
Design a resonator 606_1, . . ., 606_N for a conductive layer 206 of an FSS 200 by performing full-wave electromagnetic (EM) simulations in conjunction with circuit based simulations, wherein the slot resonator 606_1, . . ., 606_N has element values C_{606}, L_{606} that match the element values C_1, L_1 obtained in the previous step 1004 1006
Design the capacitive conductors 406_1, . . ., 406_N for conductive layers 202, 210 of an FSS 200 by performing full-wave simulations of a unit cell of a proposed FSS, wherein the capacitive conductor 406_1, . . ., 406_N have element values C_{406} that match the element value C_2 obtained in the previous step 1004 1008
End 1010

FIG. 10

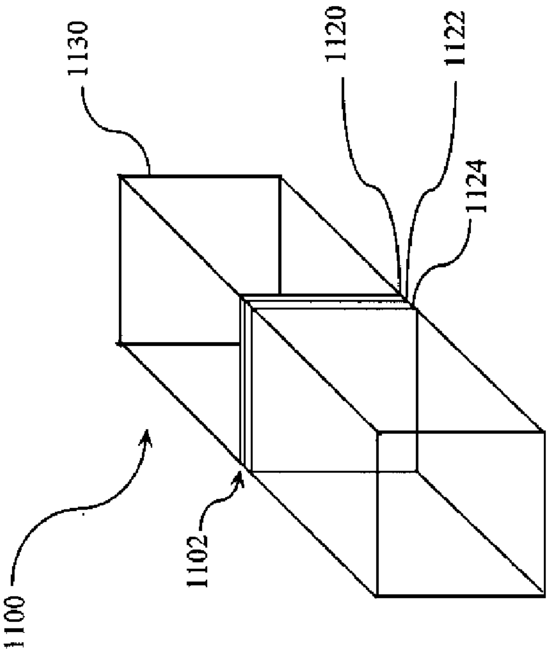


FIG. 11A
(Prior Art)

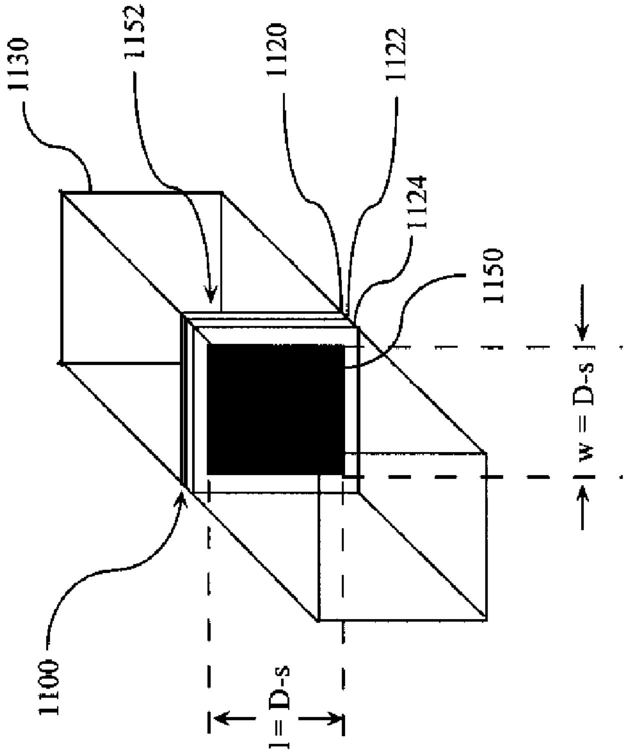


FIG. 11B

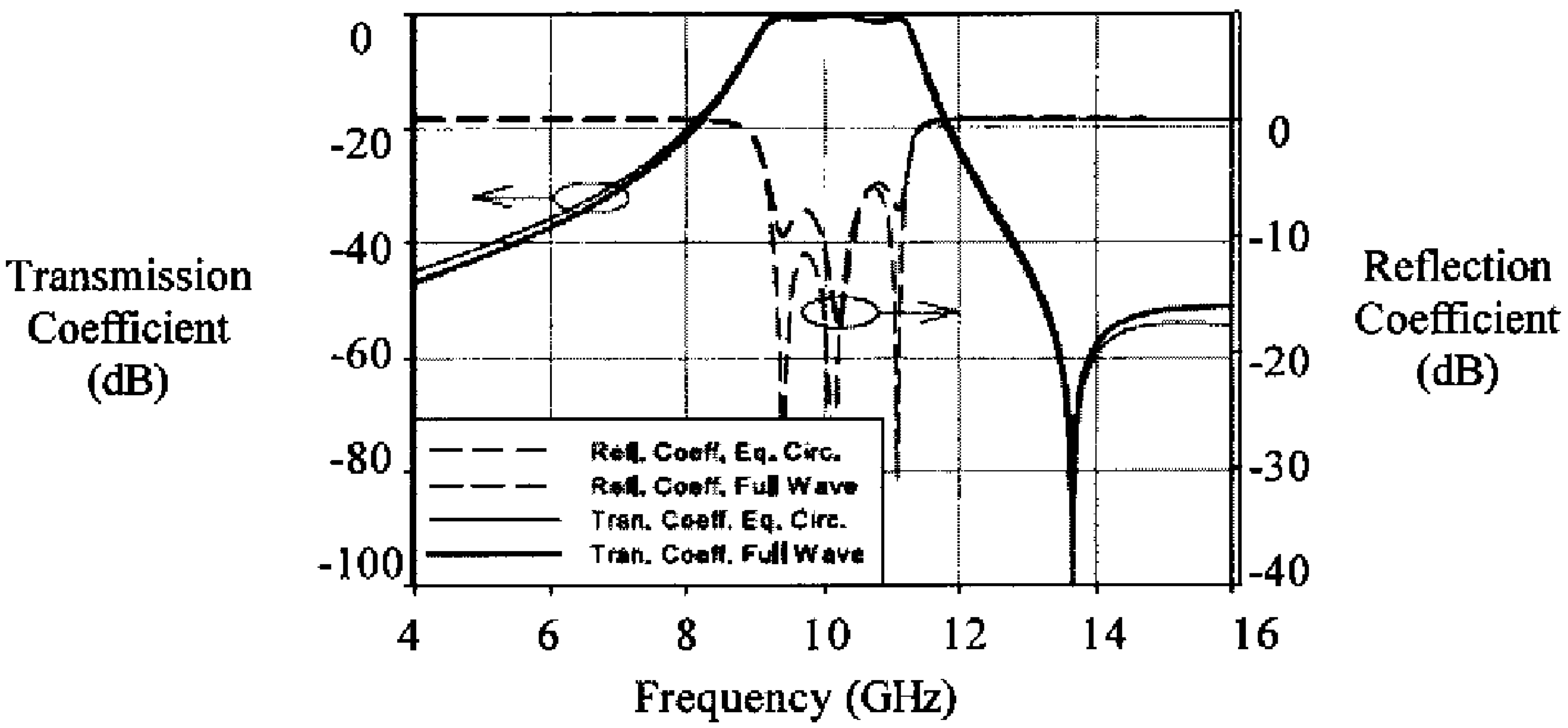

Transmission Coefficient (dB)
Reflection Coefficient (dB)
Frequency (GHz)
0
-20
-40
-60
-80
-100
0
-10
-20
-30
-40
4
6
8
10
12
14
16
Refl. Coeff. Eq. Circ.
Refl. Coeff. Full Wave
Tran. Coeff. Eq. Circ.
Tran. Coeff. Full Wave

FIG. 12

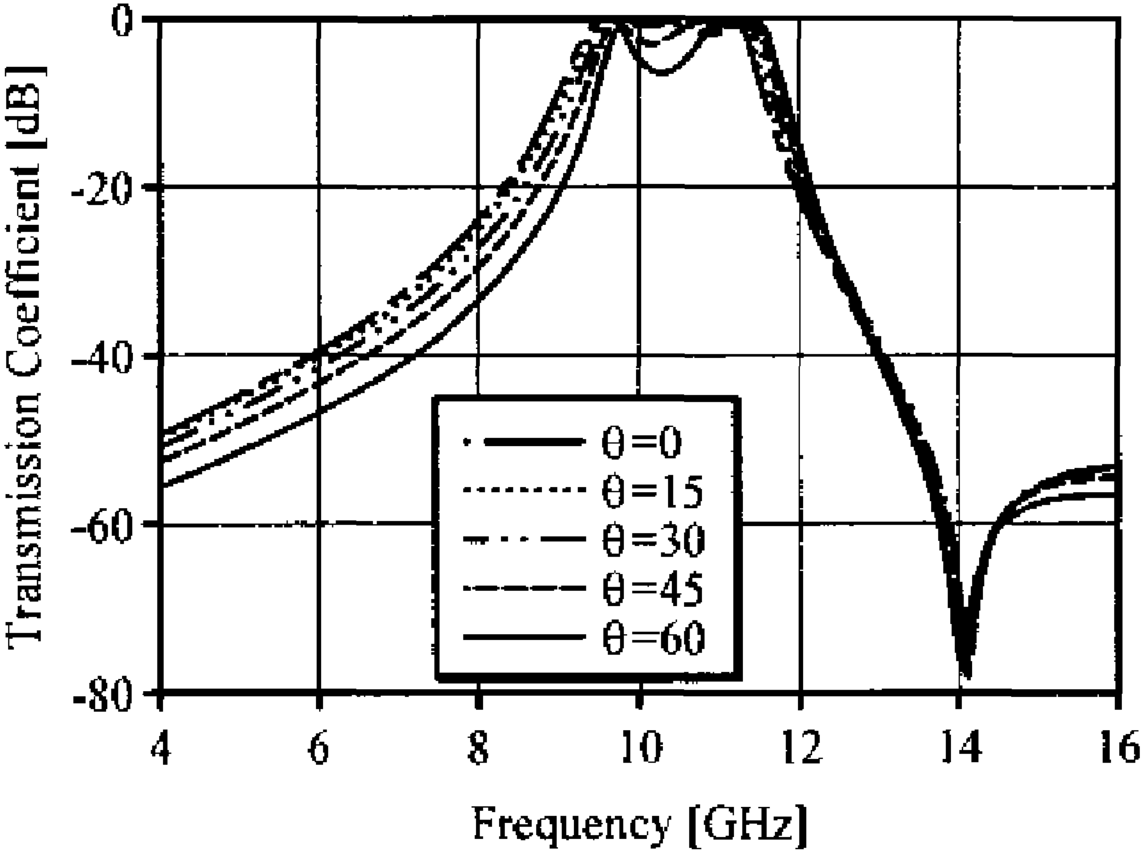

0
-20
-40
-60
-80
Transmission Coefficient [dB]
4
6
8
10
12
14
16
Frequency [GHz]
θ=0
θ=15
θ=30
θ=45
θ=60

FIG. 13

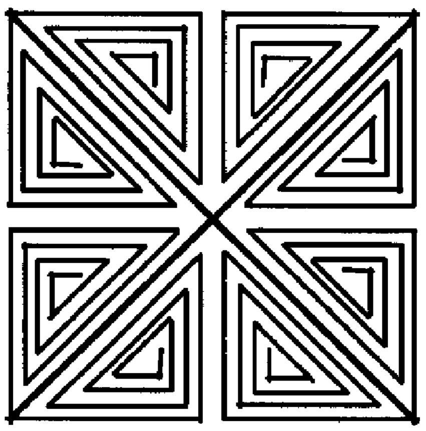


FIG. 15

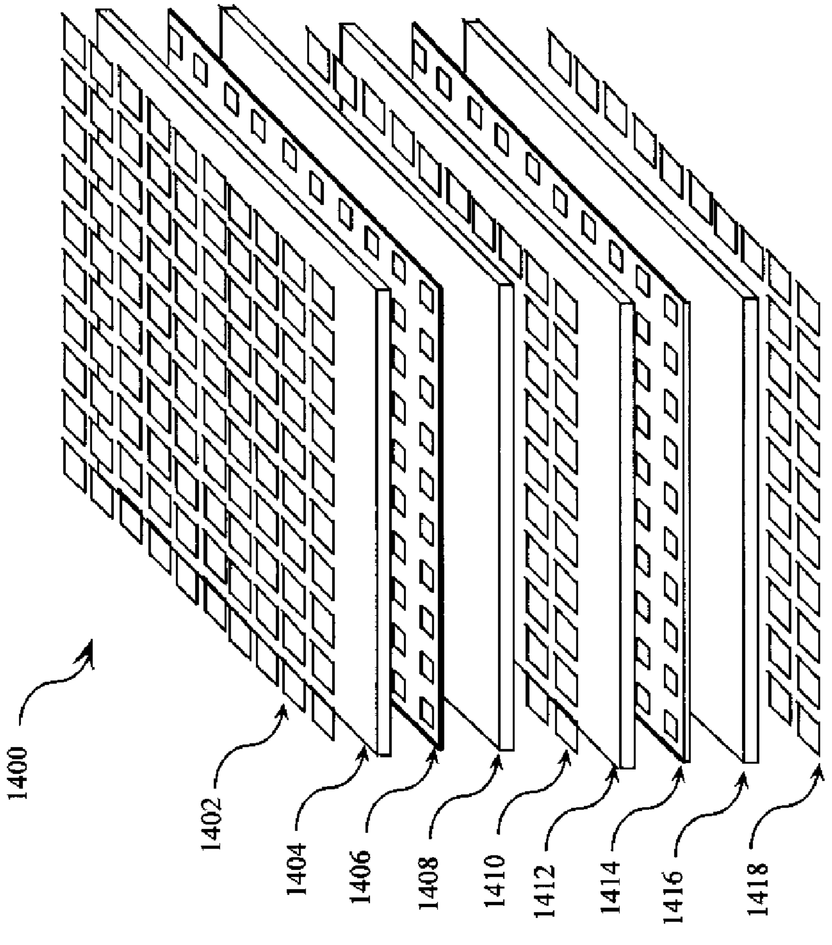


FIG. 14

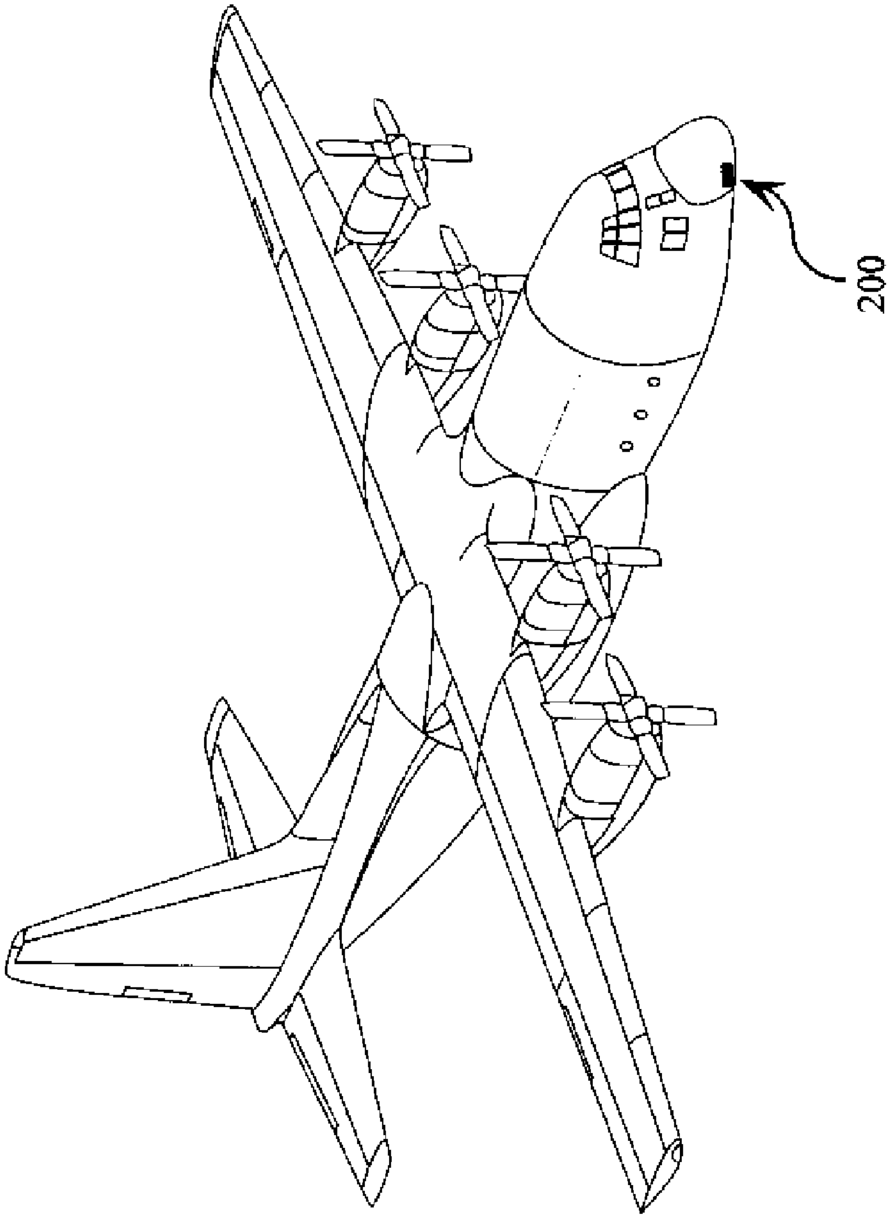


FIG. 16

LOW-PROFILE FREQUENCY SELECTIVE SURFACE BASED DEVICE AND METHODS OF MAKING THE SAME

BACKGROUND

1. Statement of the Technical Field

The invention concerns frequency selective surfaces (FSSs). More particularly, the invention concerns FSS based devices and methods of making the same.

2. Background

FSSs are surface constructions generally comprising a periodic array of electrically conductive elements. As known in the art, in order for its structure to affect electromagnetic waves (EMs), the FSS must have structural features at least as small, and generally significantly smaller, as compared to the wavelength of the electromagnetic radiation it interacts with.

FSSs are typically used in a variety of antenna applications. Such antenna applications include, but are not limited to, radome applications, Dichroic sub-reflector applications, reflect array lens applications, spatial microwave applications, optical filter applications, radio frequency identification (RFID) tag applications, collision avoidance applications, waveguide applications, and low probability of intercept system applications.

A schematic illustration of a conventional multi-layer FSS **100** configured to achieve a higher-order filter response is shown in FIG. **1**. The phrase “higher-order”, as used herein, refers to an order greater than a first-order. As known in the art, in order to achieve a higher-order filter response, a plurality of first-order FSSs are cascaded by stacking respective FSSs to have a quarter wavelength spacing between each other.

FSS **100** is a third-order band-pass FSS and includes three (3) first-order FSSs $\mathbf{102}_1, \ldots, \mathbf{102}_3$ separated by two (2) dielectric layers $\mathbf{104}_1$, $\mathbf{104}_2$. Each of the first-order FSSs $\mathbf{102}_1, \ldots, \mathbf{102}_3$ can comprise an array of dipole or slot antennas that act as resonators around an operating frequency (e.g., 10 GHz) of the multi-layer FSS. Each of the dielectric layers $\mathbf{104}_1$, $\mathbf{104}_2$ act as an impedance inverter. The first-order FSSs $\mathbf{102}_1, \ldots, \mathbf{102}_3$ are cascaded so as to have a certain distance d between each other. The distance d is a physical distance defined by the physical thickness of the respective dielectric layer $\mathbf{104}_1$, $\mathbf{104}_2$. The physical distance d typically has a value which corresponds to an electrical thickness of one-fourth of a wavelength (λ/4). For a frequency of ten gigahertz (10 GHz), one millimeter (1 mm) corresponds to one-thirtieth of a wavelength (λ/30). The third-order band-pass FSS **100** has an overall physical thickness t_{100}. The physical thickness t_{100} is defined by the collective physical thickness of the two (2) dielectric layers $\mathbf{104}_1$, $\mathbf{104}_2$ since the FSS layers have negligible physical thicknesses in relation to the dielectric layers. The physical thickness t_{100} typically has a value that corresponds to an electrical thickness of one-half of a wavelength (λ/2). Thus, the physical thickness t_{100} of a multi-layer FSS increases linearly as the order of the FSS increases.

Notably, conventional FSSs (such as the FSS **100** of FIG. **1**) suffer from certain known deficiencies. For example, the significant physical thickness t_{100} of the conventional FSS **100** results in an undesirable sensitivity of its response to the angle of incidence of the radiation. Also, the physical thickness t_{100} of conventional multi-layer FSS **100** limits its applications, including applications where conformal FSSs are required. Therefore, there is a need for an improved higher-order FSS design.

SUMMARY

This Summary is provided to comply with 37 C.F.R. § 1.73, requiring a summary of the invention briefly indicating the nature and substance of the invention. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

Embodiments of the present invention concern frequency selective surface-based (FSS-based) devices for processing electromagnetic waves. The FSS-based device comprises at least three (3) FSSs. A first FSS has a first primary resonant frequency and a second FSS has a second primary resonant frequency. The FSS-based device also comprises a high quality factor (Q) FSS interposed between the first and second FSSs. The high Q FSS has a lower primary resonant frequency relative to the first and second primary resonant frequencies, which are generally at least thirty percent (30%) higher as compared to the high Q FSS. The high Q FSS has a loaded quality factor of at least thirty at its primary resonant frequency. The FSS-based device also comprises a first and second dielectric layer. The first dielectric layer is interposed between the first FSS and the high Q FSS, and the second dielectric layer is interposed between the second FSS and the high Q FSS. Significantly, the electrical thickness of the dielectric layers can be less than a twentieth of a wavelength (λ/20), or about at least an order of magnitude less than conventional multi-layers FSS designs. As a result, embodiments of the invention provide low-profile devices.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will be described with reference to the following drawing figures, wherein like numerals represent like items throughout the figures, and in which:

FIG. **1** is a schematic illustration of a conventional multi-layer third-order frequency selective surface (FSS).

FIG. **2** is a schematic illustration of a multi-layer third-order low profile FSS topology according to an embodiment of the invention.

FIG. **3** is an enlarged side view of the multi-layer third-order low profile FSS of FIG. **2**.

FIG. **4** is an enlarged top view of an FSS of the third-order low profile frequency selective surface shown in FIGS. **2**-**3**.

FIG. **5** is an enlarged top view of an array of electrically conductive elements shown in FIG. **4**.

FIG. **6** is an enlarged top view of a high quality factor FSS of the third-order low profile frequency selective surface shown in FIGS. **2**-**3**.

FIG. **7** is an enlarged top view of an array of slot antenna apertures shown in FIG. **6**.

FIG. **8** is an enlarged top view of a slot antenna shown in FIGS. **6**-**7**.

FIG. **9**A is a first exemplary equivalent circuit for the multi-layer third-order low profile FSS shown in FIGS. **2**-**3**.

FIG. **9**B is a second exemplary equivalent circuit for the multi-layer third-order low profile FSS shown in FIGS. **2**-**3**.

FIG. **10** is a flow diagram of a design process according to an embodiment of the invention for designing the multi-layer third-order low profile FSS shown in FIGS. **2**-**3**.

FIG. **11**A is a schematic illustration of a transmission line model of a slot antenna loaded with a lumped capacitor.

FIG. **11**B is a schematic illustration of a transmission line model of the equivalent circuit shown in FIG. **9**A.

FIG. **12** is a graph illustrating a frequency response of an FSS according to an embodiment of the invention obtained from full-wave electromagnetic simulations and frequency responses predicted by an equivalent circuit model.

FIG. **13** is a graph illustrating a transmission coefficient of an FSS according to an embodiment of the invention for an obliquely incident plane wave for various angles of incidence ranging from θ=0° to 60°.

FIG. **14** is a schematic illustration of a multi-layer fifth-order FSS according to an embodiment of the invention.

FIG. **15** is an enlarged top view of a slot antenna according to an embodiment of the invention.

FIG. **16** is schematic illustration of an airplane with the FSS of FIGS. **2-3** disposed thereon.

DETAILED DESCRIPTION

Embodiments of the invention provide low profile, multi-layer frequency selective surfaces (FSSs) for use in applications including filter applications, reflector applications, and transmission applications. In the filter applications, the low profile, multi-layer FSSs are designed to have higher-order filter responses (e.g., higher order bandpass frequency responses). The phrase "higher-order filter responses", as used herein, refers to an N^{th}-order filter response, where N has a value equal to or greater than three (e.g., N=3, 4, 5, 6, 7, . . .). The N^{th}-order multi-layer FSSs have physical thicknesses t_N less than the physical thicknesses t_C of N^{th}-order conventional multi-layer FSSs (e.g., t_N<a value that corresponds to an electrical thickness of 0.1λ and t_C>a value that corresponds to an electrical thickness of 0.5λ, where 1 mm corresponds to λ/30 for a frequency of 10 GHz). As such, the N^{th}-order multi-layer FSSs can be used in applications where conformal multi-layer FSSs are required. Such applications include, but are not limited to, aircraft applications, missile applications, ship applications, and other propelled object or vehicle applications. FSSs according to embodiments of the invention have been found to provide low sensitivity's of response to angles of incidence of an incident plane wave. The low-profile, multi-layer FSSs can also be used in antenna applications, radome applications, beam former applications for large antenna arrays, radar cross section reduction applications, spaceborne deployable antenna array applications, electronic counter measure (ECM) applications, and electronic counter measure (ECCM) applications.

The invention will now be described more fully hereinafter with reference to accompanying drawings, in which illustrative embodiments of the invention are shown. This invention, may however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

Referring now to FIG. **2**, there is provided an enlarged perspective view of a third-order frequency selective surface (FSS) **200** topology according to an embodiment of the invention. A side view of a third-order FSS **200** is provided in FIG. **3**. The third-order FSS **200** acts as a spatial band-pass filter with a third-order band-pass response. The phrase "third-order band-pass response", as used herein, refers to a filter response characteristic of a third-order system which comprises a sharper out-of-band rejection response as compared to the rejection provided by a second or first-order band-pass filter. Spatial band-pass filters are well known to those having ordinary skill in the art, and therefore will not be described herein. The third-order FSS **200** can be fabricated using any suitable fabrication technique known to those having ordinary skill in the art (e.g., a lithography technique).

Although the present invention will be described in relation to a third-order FSS **200**, the invention is not limited in this regard. The following discussion of the third-order FSS **200** is sufficient for understanding the characteristics and features of other low profile N^{th}-order FSSs, where N has a value equal to or greater than three (e.g., N=5, 6, 7, . . .). In this regard, it should be understood that the basic topology of the third-order FSS **200** can be cascaded to obtain higher-order frequency responses N (e.g., N=5, 6, 7, . . .). As noted above, the term "cascade", as used herein, refers to a stacked arrangement of FSSs.

Referring now to FIGS. **2-3**, the third-order FSS **200** is comprised of FSSs **202**, **210**, a high quality factor (Q) FSS **206**, and dielectric layers **204**, **208**. The dielectric layer **204** is disposed between the FSS **202** and high Q FSS **206**. The features on FSSs **202**, **206** have respective dimensions including physical thicknesses t_{202}, t_{206} and spacing's between one another selected in accordance with a particular third-order FSS **200** application (including application frequency). Similarly, the dielectric layer **208** is disposed between the high Q FSS **206** and FSS **210**. The features of FSS **210** have dimensions including a physical thickness t_{210} selected in accordance with a particular third-order FSS **200** application. The dielectric layers **204**, **208** can be formed of the same dielectric material or different dielectric materials. The dielectric layers **204**, **208** have respective dimensions including physical thicknesses t_{204}, t_{208} selected in accordance with a particular third-order FSS **200** application. The particular application may also include the selection of the electrically conductive and dielectric materials used to fabricate FSS **200**

The high Q FSS has a minimum quality factor Q at its primary resonant frequency. As should be understood, the phrase "quality factor" as used herein refers to a measure for the strength of a damping of a resonator's oscillations and a measure for a relative line-width of a resonator. The loaded quality factor Q can have a minimum value of at least thirty (30) as its primary resonant frequency. As should also be understood, the phrase "loaded quality factor", as used herein, refers to a specific mode of resonance of an FSS when there is external coupling to that mode. The high Q FSS **206** can have a primary resonant frequency that is lower than the primary resonant frequencies of the FSSs **202**, **210**. Accordingly, the high Q FSS **206** can resonate at a frequency of operation while the FSSs **202** and **210** (above and below FSS **206**) can be non-resonant since their operation will be below their primary resonant frequency. The primary resonant frequency for FSS **206** can generally be selected to have a value ranging between five hundred megahertz to one hundred gigahertz (500 MHz-100 GHz).

According to an embodiment of the invention, the FSSs **202**, **210** each have a resonant frequency of at least thirty percent (30%) higher or 1.3 times the primary resonant frequency of the high Q FSS **206**. For example, the FSSs **202**, **210** each can have a resonant frequency three (3) times higher than the resonant frequency of the high Q FSS **206**. The invention is not limited in this regard.

The third-order FSS **200** has an overall physical thickness t_{200}. This physical thickness t_{200} is substantially less than the overall physical thickness of a conventional third-order FSS (such as the FSS shown in FIG. **1**). The phrase "substantially less" as used herein means that a physical thickness t of a conventional N^{th}-order FSS is reduced by a factor larger than or equal to fifty-percent (50%). For example, the overall physical thickness t_{200} of the third-order FSS **200** generally has a value that corresponds to an electrical thickness falling between one-tenth of a wavelength (λ/10) and one-hundredth of a wavelength (λ/100). As described above, for a frequency of ten gigahertz (10 GHz), one millimeter (1 mm) corresponds to one-thirtieth of a wavelength (λ/30). In contrast, the overall physical thickness t_{100} of the conventional third-order FSS **100** (shown in FIG. **1**) has a value that corresponds to an electrical thickness of one-half of a wavelength (λ/2). The invention is not limited in this regard. The physical thickness of an N^{th}-order FSS according to an embodiment of the invention can have any value equal to the physical thickness of an N^{th}-order conventional FSS reduced by a factor larger than or equal to fifty (or 2%).

This relatively small physical thickness t_{200} provides a low-profile third-order FSS **200** that overcomes a particular non-conformal drawback of conventional third-order FSSs (such as the third-order FSS **100** shown in FIG. **1**). Unlike conventional third-order FSSs (such as the third-order FSS shown in FIG. **1**), the low-profile third-order FSS **200** can generally be used on conformal or curved surfaces. The conformal or curved surfaces can include, but are not limited to, the curved surfaces of aircrafts, missiles, ships, and other propelled object or vehicles. A schematic illustration of the low-profile third-order FSS **200** used on a curved surface of the nose of an aircraft is shown in FIG. **16**.

Each FSS **202**, **206**, **210** of the third-order FSS **200** can generally be a two-dimensional periodic structure with sub-wavelength unit cell dimensions and/or periodicity. The phrase "unit cell" as used herein refers to a combination of resonant and non-resonant elements. The electrically small period and unit cell dimensions of the third-order FSS **200** allow for localization of band-pass characteristics to within a small area on a surface of the third-order FSS **200**. This localization of band-pass characteristics facilitates flexible spatial filtering for an arbitrary wave phase-front. The small unit cell dimensions and overall physical thickness t_{200} of the third-order FSS **200** generally results in a reduced sensitivity to an angle of incidence of an electromagnetic (EM) wave as compared to conventional third-order FSSs (such as the third-order FSS shown in FIG. **1**). The sub-wavelength periodic structure allows for reducing an overall two-dimensional (2D) size of the third-order FSS **200**. For example, if the third-order FSS **200** includes a sub-wavelength periodic structure, then the third-order FSS **200** can have an overall two-dimensional (2D) area corresponding to an electrical area of two wavelengths by two wavelengths (2λ by 2λ). The invention is not limited in this regard. The third-order FSS **200** can have an overall two-dimensional (2D) area selected in accordance with a particular third-order FSS **200** application. For example, if a two-dimensional (2D) area of an FSS **200** is defined by the dimensions of fifteen unit cells by fifteen unit cells, then the frequency response of the FSS **200** is a substantially infinite frequency response. Therefore, a desired frequency response can be obtained for a two-dimensional (2D) area defined by the dimensions of less than fifteen unit cells by fifteen unit cells.

A pair of third-order FSSs **200** can be stacked by sharing a common FSS layer to provide a higher than third-order FSS, such as a fifth-order FSS. The fifth-order FSS can have a low-profile (or physical thickness) corresponding to an electrical thickness on the order of one-fifth of a wavelength ($\lambda/5$) to a fiftieth of a wavelength ($\lambda/50$). This low-profile (or physical thickness) is substantially less than the profile (or physical thickness) of a conventional fifth-order FSS (i.e., a physical thickness of fifth-order FSS is above a wavelength). A schematic illustration of a fifth-order FSS **1400** according to an embodiment of the invention is provided in FIG. **14**. As shown in FIG. **14**, the first third-order FSS comprises FSSs **1410**, **1406**, and **1402** while the second third-order FSS comprises FSSs **1418**, **1414**, and **1410**. FSSs **1406** and **1414** are the high Q FSS. Fifth-order FSS **1400** comprises dielectric layers **1404**, **1408**, **1412**, **1416**. The dielectric layers **1404**, **1408**, **1412**, **1416** can be formed of the same dielectric material. The FSSs **1402**, **1418** can include identical arrays of metallic elements. The FSS **1410** can have a capacitance greater than the capacitance of the FSSs **1402**, **1418**. The FSSs **1406**, **1414** can be comprised of the same array of features (or "resonators"). The FSSs **1406**, **1414** can have a primary resonant frequency lower than the primary resonant frequencies of the FSSs **1402**, **1412**, **1418**. Accordingly, the FSSs **1406**, **1414** can resonate at a frequency of operation having a value between five hundred megahertz to one hundred gigahertz (500 MHz-100 GHz). In contrast, the FSSs **1402**, **1412**, **1418** may not resonate at the frequency of operation. The invention is not limited in this regard.

An enlarged top view of the FSS **202** is provided in FIG. **4**. It should be understood that the FSS **210** can be the same as or substantially similar to the FSS **202**. As such, the following discussion of the FSS **202** is generally sufficient for understanding the FSS **210**.

Referring now to FIG. **4**, the FSS **202** shown is generally a two-dimensional periodic structure with an array **406** of electrically conductive elements $\mathbf{406}_1, \ldots, \mathbf{406}_N$. The array **406** can include a plurality of periodic electrically conductive structures (e.g., patches) disposed (or printed) on a dielectric layer **204** (described above in relation to FIGS. **2-3**) of the FSS **200** or embedded in the dielectric layer **204**. The periodic metallic structures (e.g., patches) can be disposed on the dielectric layer **204** using any suitable technique known in the art. Such techniques can include, but are not limited to, printing techniques and adhesion techniques. Each of the electrically conductive elements $\mathbf{406}_1, \ldots, \mathbf{406}_N$ can be formed of an electrically conductive material, such as metal. The array **406** can have a pre-selected length **402** and width **404**. Each of the dimensions **402**, **404** is selected in accordance with a particular third-order FSS **200** application.

An enlarged top view of electrically conductive elements $\mathbf{406}_1$, $\mathbf{406}_2$, $\mathbf{406}_3$, $\mathbf{406}_{11}$, $\mathbf{406}_{12}$, $\mathbf{406}_{21}$, $\mathbf{406}_{22}$, $\mathbf{406}_{23}$ is provided in FIG. **5**. It should be understood that the following discussion is sufficient for understanding the geometries of each electrically conductive element $\mathbf{406}_1, \ldots, \mathbf{406}_N$ and inter-element spacing of the electrically conductive elements $\mathbf{406}_1, \ldots, \mathbf{406}_N$. It should also be understood that the geometries and inter-element spacing contribute to a determination of an overall frequency response of FSS **202** and thus the third-order FSS **200**. As such, each of the electrically conductive elements can have an arbitrary geometry selected in accordance with a particular FSS **200** application. Such an arbitrary geometry can include, but is not limited to, a rectangular geometry (such as the square geometry shown in FIGS. **4-5**) and a rectangular geometry with at least one set of digits (not shown).

As shown in FIG. **5**, each unit cell **500** has a pre-selected physical length D_y and physical width D_x. The physical length D_y has a maximum value corresponding to an electrical dimension equal to a period of the third-order FSS **200** in a y direction of a two-dimensional (2D) space. Similarly, the physical width D_x has a maximum value corresponding to an electrical dimension equal to a period of the third-order FSS **200** in an x direction of a two-dimensional (2D) space. Each unit cell **500** is comprised of a dielectric portion with a preselective physical width $d=s/2$, where s is the distance between adjacent electrically conductive elements. Each unit cell **500** is also comprised of a conductive portion defined by an electrically conductive element $\mathbf{406}_1$, $\mathbf{406}_2$, $\mathbf{406}_3$, $\mathbf{406}_{11}$, $\mathbf{406}_{12}$, $\mathbf{406}_{21}$, $\mathbf{406}_{22}$, $\mathbf{406}_{23}$.

Each of the electrically conductive elements $\mathbf{406}_1$, $\mathbf{406}_2$, $\mathbf{406}_3$, $\mathbf{406}_{11}$, $\mathbf{406}_{12}$, $\mathbf{406}_{21}$, $\mathbf{406}_{22}$, $\mathbf{406}_{23}$ is separated from adjacent electrically conductive elements by a pre-selected physical distance $d=s$. Each of the electrically conductive elements $\mathbf{406}_1$, $\mathbf{406}_2$, $\mathbf{406}_3$, $\mathbf{406}_{11}$, $\mathbf{406}_{12}$, $\mathbf{406}_{21}$, $\mathbf{406}_{22}$, $\mathbf{406}_{23}$ has a pre-selected length D_y-s and width D_x-s. Each of the dimensions D_y−s, D_x−s is selected in accordance with a particular FSS **200** application. For example, each of the dimensions has D_y−s, D_x−s corresponding to an electrical dimension of less than one-wavelength. In effect, the FSS **202** comprising electrically conductive elements **406**$_1$, **406**$_2$, **406**$_3$, **406**$_{11}$, **406**$_{12}$, **406**$_{21}$, **406**$_{22}$, and **406**$_{23}$ is non-resonant at a frequency of operation (e.g., 10 GHz). The periodic arrangement of the electrically conductive elements **406**$_1$, **406**$_2$, **406**$_3$, **406**$_{11}$, **406**$_{12}$, **406**$_{21}$, **406**$_{22}$, **406**$_{23}$ presents a capacitive impedance in both directions to an incident electromagnetic (EM) wave.

Referring now to FIG. **6**, there is provided an enlarged top view of the high Q FSS **206** shown in FIGS. **2-3**. The high Q FSS **206** can generally be defined as a two-dimensional periodic structure with an array **606** of dielectric features **606**$_1$, . . . , **606**$_N$. The array **606** of features **606**$_1$, . . . , **606**$_N$ can be etched in an electrically conductive layer using any suitable etching technique known in the art. Each of the dielectric features **606**$_1$, . . . , **606**$_N$ can generally comprise a slot resonator. The array **406** of features **606**$_1$, . . . , **606**$_N$ can have pre-selected dimensions, such as a physical length **602** and a physical width **604**. Each of the dimensions **602**, **604** is selected in accordance with a particular third-order FSS **200** application.

An enlarged top view of features **606**$_1$, **606**$_2$, **606**$_3$, **606**$_{11}$, **606**$_{12}$, **606**$_{21}$, **606**$_{22}$, **606**$_{23}$ is provided in FIG. **7**. It should be understood that the following discussion is sufficient for understanding the geometries of each feature **606**$_1$, . . . , **606**$_N$ and inter-element spacing of the features **606**$_1$, . . . , **606**$_N$. It should also be understood that the geometries and inter-element spacing contribute to a determination of an overall frequency response of the third-order FSS **200**. As such, each of the features **606**$_1$, . . . , **606**$_N$ can have an arbitrary geometry selected in accordance with a particular FSS **200** application. A schematic illustration of a feature **606**$_1$ having a first type of geometry according to an embodiment of the invention is provided in FIG. **8**. A schematic illustration of a feature having a second type of geometry according to an embodiment of the invention is provided in FIG. **15**. It should be noted that the feature shown in FIG. **15** is a dual-polarized crossed slot antenna comprising two straight slots arranged so as to form a cross, wherein each straight slot is connected to two (2) balanced spirals at each of its ends.

Referring now to FIG. **8**, the feature **606**$_1$ has an exemplary arbitrary geometry defined by electrically conductive portions including a straight slot section **802** connected to two (2) balanced spirals **804**, **806** at each end **808**, **810**. The straight slot section **802** has a physical width of D_K selected in accordance with a particular third-order FSS **200** application. Each spiral of the spirals **804** is separated from an adjacent spiral of the spirals **806** by a certain physical distance D_M. The physical distance D_M is also selected in accordance with a particular third-order FSS **200** application.

The effective electrical length E_1 of the feature **606**$_1$ extends from a first end of a first balanced spiral **820** to the corresponding end of a second balanced spiral **822**. According to an embodiment of the invention, the effective electrical length E_1 of the feature **606**$_1$ has a value equal to half of a wavelength ($\lambda/2$). In such a scenario, the feature **606**$_1$ is a resonant structure acting as a magnetic Herzian dipole. Magnetic Herzian dipoles are well known to those having ordinary skill in the art, and therefore will not be described herein. The invention is not limited in this regard. The effective electrical length E_1 of the feature **606**$_1$ can have any value selected in accordance with a particular third-order FSS application.

Referring again to FIG. **7**, each of the features **606**$_1$, **606**$_2$, **606**$_3$, **606**$_{11}$, **606**$_{12}$, **606**$_{21}$, **606**$_{22}$, **606**$_{23}$ has the same overall physical length and physical width having values equal to D_{ap}. In this regard, it should be understood that the overall area of a feature is significantly smaller than a conventional dipole or slot antenna of a first-order FSS (such as that shown in FIG. **1**). For example, each features **606**$_1$, **606**$_2$, **606**$_3$, **606**$_{11}$, **606**$_{12}$, **606**$_{21}$, **606**$_{22}$, **606**$_{23}$ has an overall physical area of $D_{ap} \times D_{ap}$, where D_{ap} is a fraction of a unit cell size, i.e., $D_{ap} < D_x$, D_y. Each of the features **606**$_1$, **606**$_2$, **606**$_3$, **606**$_{11}$, **606**$_{12}$, **606**$_{21}$, **606**$_{22}$, **606**$_{23}$ is a single polarized feature capable of resonating an electric field polarized in a "y" direction of a two-dimensional (2D) space **700**. In effect, the frequency response of the third-order FSS **200** becomes polarization sensitive.

Referring now to FIG. **9**A, there is provided an equivalent circuit **900** for the third-order FSS **200** (described above in relation to FIGS. **2-7**). The equivalent circuit **900** is generally that of a third-order band-pass microwave filter. The operations of a third-order band-pass microwave filter are well known to those having ordinary skill in the art, and therefore will not be described herein. However, a brief discussion of the equivalent circuit **900** is provided to assist a reader in understanding the present invention.

As shown in FIG. **9**A, the equivalent circuit **900** is comprised of an input terminal **902**, an output terminal **904**, capacitors **920**, **924**, an inductor **926**, a feature **950**, and short sections of a transmission line (SSTL) **960**, **962**, **964**, **966**. The capacitors **920**, **924** are connected in parallel between terminals **902**, **904** and ground. Each of the capacitors **920**, **924** has a capacitance C_2.

The feature **950** is a circuit equivalent of a feature **606**$_1$, . . . , **606**$_N$ (described above in relation to FIGS. **6-8**). As shown in FIG. **9**A, the feature **950** is comprised of a capacitor **922** connected in parallel with an inductor **928**. The capacitor **922** has a capacitance C_1. The inductor **928** has an inductance L_1. The feature **950** is connected in series with the inductor **926** having an inductance L_2. The inductor **926** represents a parasitic inductance associated with an electric current flowing in a ground plane of the high Q FSS **206** (described above in relation to FIGS. **6-8**), wherein resonant slots are etched in the ground plane. Each of these slots defines a slot antenna. The slot antenna resonates at a frequency determined by the shape of the resonant slots. The inductor **926** is associated with the electric current which has an inductance value inversely proportional to the cross sectional area of the conductor.

The feature **950** is connected in parallel with the capacitors **920**, **924**. The capacitors **920**, **924** represent FSSs **202**, **210** (described above in relation to FIGS. **2-3**) of the third-order FSS **200** (described above in relation to FIGS. **2-3**). The feature **950** is separated from the capacitors **920**, **924** with SSTLs **962**, **964**, respectively. The SSTLs **962**, **964** represent the dielectric layer **204**, **208** (described above in relation to FIGS. **2-3**) of the third-order FSS **200** (described above in relation to FIGS. **2-3**). As such, each of the SSTLs **962**, **964** has a characteristic impedance Z_1 and a length l. The length l of each SSTLs **962**, **964** has a value equal to the physical thickness t_{204}, t_{206} of a dielectric layer **204**, **208** (described above in relation to FIGS. **2-3**). The characteristic impedance Z_1 of each SSTLs **962**, **964** can be defined by the following mathematical equation (1).

$$Z_1 = Z_0/(\in_r)^{1/2} \qquad (1)$$

where Z_0 equals three hundred seventy-seven ohms (the impedance of free space). $\in_r$ is a dielectric constant of dielectric layers **204**, **208** (described above in relation to FIGS. **2-3**).

The SSTLs **960**, **966** represent free space provided on both sides of the third-order FSS **200** (described above in relation to FIGS. **2**-**3**). Each of the SSTLs **960**, **966** is a semi-infinite transmission line with a characteristic impedance Z_0.

Although not required to practice the invention, applicant provides the following theoretical background which is helpful to explain the operations of the multi-layer FSS structure **200**. Referring now to FIG. **9**B, there is provided an expanded equivalent circuit model **990** for the third-order FSS **200** (described above in relation to FIGS. **2**-**7**). As shown in FIG. **9**B, the equivalent circuit **990** is comprised of impendence inverters **972**, **974**, capacitive loaded transmission lines (CLTLs) **970**, **976**, and a parallel LC resonator **978**. Each of the impendence inverters **972**, **974** is an inductive network with a transmission line having a "negative" electrical length. The principles and operation of impendence inverters are well known to those having ordinary skill in the art, and therefore will not be described herein. Each of the impendence inverters **972**, **974** is interposed between a respective CLTL **970**, **976** and the parallel LC resonator **978**. The combination of these circuit components **970**, **972**, **974**, **976**, **978** results in a third-order band-pass filter. By comparing the equivalent circuits **900**, **990**, it is observed that the "negative" electrical length of each transmission line used in the impendence inverters **972**, **974** is absorbed in a "positive" electrical length of a respective CLTL **970**, **976**. The inductors L_i of the impendence inverters **972**, **974** are absorbed in the parallel LC resonator **978**.

The following FIG. **10** and accompanying text illustrate a design process **1000** for designing an N^{th}-order FSS according to an embodiment of the invention (such as the third-order FSS **200** of FIGS. **2**-**8**). It should be appreciated, however, that the design process disclosed herein is provided for purposes of illustration only and that the present invention is not limited solely to the design process shown.

Referring now to FIG. **10**, the design process **1000** begins at step **1002** and continues with step **1004**. In step **1004**, element values C_1, C_2, L_1, L_2, Z_0, Z_1, 1, $\in_r$ are obtained for an equivalent circuit **900**. These element values can be obtained using any suitable circuit simulation software known to those having ordinary skill in the art. Such circuit simulation software includes, but is not limited to, Advanced Design Systems available from Agilent Technologies of Santa Clara, Calif.

According to an embodiment of the invention, each of the dielectric layers **204**, **208** of a third-order FSS **200** is formed of a dielectric substrate having a physical thickness of half a millimeter (t_{204}=0.5 mm, t_{206}=0.5 mm). The equivalent circuit **900** has a band-pass frequency response with a center frequency of operation of ten gigahertz (10 GHz) and a fractional bandwidth of twenty percent (20%). In such a scenario, the equivalent circuit **900** element values obtained in step **1004** of design process **1000** can be defined as: C_1=22.2 pF; C_2 0.38 pF; L_1=108 pH; L_2=147 pH; Z_0=377Ω; Z_1=254Ω; 1=0.5 mm; and $\in_r$=2.2. The invention is not limited in this regard.

Referring again to FIG. **10**, the design process **1000** continues with step **1006**. In step **1006**, a feature **606**$_1$, . . . , **606**$_N$ is designed for a high Q FSS **206** (described above in relation to FIGS. **2**-**3**) of a third-order FSS **200** (described above in relation to FIGS. **2**-**3**). The feature **606**$_1$, . . . , **606**$_N$ can be designed by performing full-wave electromagnetic (EM) simulations in conjunction with a circuit based simulation. The feature **606**$_1$, . . . , **606**$_N$ can be designed so that it has element values C_{606}, L_{606} matching the element values C_1, L_1 obtained in the previous step **1004**.

According to an embodiment of the invention, the feature **606**$_1$, . . . , **606**$_N$ can generally be a slot antenna composed of a straight slot section **802** connected to two (2) balanced spirals **804**, **806** at each end **808**, **810**. The effective electrical length E_1 of the feature **606**$_1$ has a value approximately equal to half of a wavelength (λ/2). As such, the feature **606**$_1$ is a resonant structure acting as a magnetic Herzian dipole. The quality factor Q of the feature **606**$_1$, . . . **606**$_N$ is inversely proportional to the area ($D_{ap}\cdot D_{ap}$) occupied by the features **606**$_1$, . . . , **606**$_N$. The quality factor Q of the features **606**$_1$, . . . , **606**$_N$ can be increased by reducing the area ($D_{ap}\cdot D_{ap}$) occupied by the features **606**$_1$, . . . , **606**$_N$ while maintaining the resonant frequency of the features **606**$_1$, . . . **606**$_N$In effect, the desired element values L_1, C_1 can be obtained by selecting aperture dimensions of the features **606**$_1$, . . . , **606**$_N$ for a constant resonant frequency. The invention is not limited in this regard.

According to an embodiment of the invention, step **1006** involves designing a feature **606**$_1$, . . . , **606**$_N$ using full-wave electromagnetic (FWEM) simulations in conjunction with circuit based simulation. In such a scenario, a portion of a unit cell (PUC) of a proposed third-order FSS is simulated by performing full-wave electromagnetic (EM) simulations using HFSS® simulation software available from Ansoft Corporation of Pittsburg, Pa. A schematic illustration of a simulation model **1100** including a topology for the PUC is provided in FIG. **11**A. As shown in FIG. **11**A, the PUC **1102** can comprise a feature **1122** sandwiched between two dielectric substrates **1120**, **1124**. The PUC **1102** is placed in a waveguide **1130**. The waveguide **1130** has periodic boundary conditions for emulating an infinite structure. Step **1006** also involves performing Finite Element Method (FEM) simulations to calculate transmission and reflection coefficient of a vertically polarized transverse electromagnetic (TEM) wave. Step **1006** further involves performing a circuit based (CB) simulation of a relevant portion **910** of an equivalent circuit **900** (described above in relation to FIG. **9**A). After performing the FWEM, FEM, and CB simulations, a matching process is performed. This matching process can generally involve matching the results of the FWEM simulations to results obtained from the CB simulation. The matching process can also involve modifying the dimensions of a feature **1122** in accordance with the outcome of matching the FWEM and CB simulation results. This matching process can be iteratively performed until a frequency response obtained through the FWEM simulations are matched to the frequency response of the relevant portion **910** of an equivalent circuit **900** (described above in relation to FIG. **9**A). The invention is not limited in this regard.

Referring again to FIG. **10**, the design process **1000** continues with step **1008**. In step **1008**, the electrically conductive elements **406**$_1$, . . . , **406**$_N$ are designed for an FSS **202**, **210** (described above in relation to FIGS. **2**-**3**) of a third-order FSS **200** (described above in relation to FIGS. **2**-**3**). The electrically conductive elements **406**$_1$, . . . , **406**$_N$ can be designed by performing full-wave simulations of a unit cell for a proposed FSS. The electrically conductive elements **406**$_1$, . . . , **406**$_N$ can be designed so that they have element values C_{406} matching the element values C_2 obtained in the previous step **1004**.

According to an embodiment of the invention, the electrically conductive elements **406**$_1$, . . . , **406**$_N$ are designed by adding two (2) electrically conductive elements **1150**, **1152** to the full-wave simulation model **1100** (as shown in FIG. **11**B). The two (2) electrically conductive elements **1150**, **1152** correspond to a capacitor **920**, **924** (described above in relation to FIG. **9**A) of the equivalent circuit **900** (described above in relation to FIG. **9**A). The electrically conductive elements **1150**, **1152** are sub-wavelength, non-resonant patches with physical lengths 1=D−s and physical widths w=1=D−s, where D has a value corresponding to the period of the full-wave simulation model **1100** and s is the distance between adjacent electrically conductive elements of a proposed FSS. D can have a value equal to the physical length D_y and physical width D_x of a unit cell. The initial dimension 1 of the electrically conductive elements **1150**, **1152** is approximated using the following mathematical equation (2).

$$C=\in_0\in_{eff}[(2(D-s))/\pi]\log[1/(\sin(\pi s/(2(D-s))))] \quad (2)$$

where C is a capacitance of a electrically conductive element of an FSS measured in Farads. $\in_0$ is the permittivity of free space and has value of $8.85\cdot10^{-12}$ F/m. $\in_{eff}$ is the effective dielectric constant of the dielectric layers **204**, **208** (described above in relation to FIGS. **2-3**). D is a unit cell dimension corresponding to the periodicity of an FSS, where $D_x=D_y=Ds$ is a physical distance between two adjacent electrically conductive elements of the FSS. π has a value equal to 3.1415.

After adding the electrically conductive elements **1150**, **1152** to the full-wave simulation model **1100**, full-wave simulations are performed using the modified full-wave simulation model **1100** (as shown in FIG. **11**B). It should be noted that the modified full-wave simulation model **1100** shown in FIG. **11**B represents a unit cell of a proposed FSS. Upon completing the full-wave simulations, the physical dimensions **1**, w of the electrically conductive elements **1150**, **1152** are adjusted based on the results of the full-wave simulations. This full-wave simulation and dimension adjustment process is repeated until the frequency response of the modified full-wave simulation model **1100** matches a desirable frequency response of a proposed multi-layer FSS. The invention is not limited in this regard.

The following Example is provided in order to further illustrate the design process **1000**. The scope of the invention, however, is not to be considered limited in any way thereby.

EXAMPLE

A third-order FSS **200** having an equivalent circuit **900** was designed using design process **1000**. The circuit elements of the equivalent circuit **900** used in the design process **1000** were defined as: $C_1=22.2$ pF; $C_2=0.38$ pF; $L_1=108$ pH; $L_2=147$ pH; $Z_0=377\Omega$; $Z_1=254\Omega$; 1=0.5 mm; and $\in_r=2.2$. The physical and geometrical parameters for the third-order FSS **900** obtained during the design process **1000** were defined as: $D_x=5.5$ mm; $D_y=5.5$ mm; $t_{200}=0.5$ mm; $\in_r=2.2$; s=60 μm; and $D_{ap}=1.46$ mm.

The frequency response between four and sixteen gigahertz (4 GHz-16 GHz) of the third-order FSS **200** obtained from FWEM simulations is shown graphically in FIG. **12**. The frequency response of the equivalent circuit **900** obtained from CB simulations is also shown graphically in FIG. **12**. As shown in FIG. **12**, the equivalent circuit **900** accurately predicted the frequency response of the third-order FSS **200**. A calculated frequency response of the third-order FSS **200** for non-normal angles of incidence ($\theta=15°$, 30°, 45°, and 60°) is shown graphically in FIG. **13**. As shown in FIG. **13**, the transmission coefficient of the third-order FSS **200** is provided for an obliquely incident plane wave for various angles of incident ranges from zero degrees to sixty degrees (0° to 60°). The frequency response of the third-order FSS **200** was not considerably affected as the angle of incidence increases from zero degrees to forty-five degrees (0° to 45°). However, the frequency response of the third-order FSS **200** was affected as the angle of incidence increases from forty-five degrees to N degrees (45° to N°), where N is an integer greater than forty-five (45). Nevertheless, the structure demonstrated a rather stable frequency response as a function of angle of incidence without the aid of any dielectric superstrates that are commonly used to stabilize the frequency response of FSSs for oblique angles of incidence.

All of the apparatus, methods and algorithms disclosed and claimed herein can be made and executed without undue experimentation in light of the present disclosure. While the invention has been described in terms of preferred embodiments, it will be apparent to those of skill in the art that variations may be applied to the apparatus, methods and sequence of steps of the method without departing from the concept, spirit and scope of the invention. More specifically, it will be apparent that certain components may be added to, combined with, or substituted for the components described herein while the same or similar results would be achieved. All such similar substitutes and modifications apparent to those skilled in the art are deemed to be within the spirit, scope and concept of the invention as defined.

The Abstract of the Disclosure is provided to comply with 37 C.F.R. § 1.72(b), requiring an abstract that will allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the following claims.

I claim:

1. A frequency selective surface-based (FSS-based) device for processing electromagnetic waves, comprising:

a first and second frequency selective surface (FSS) having first and second primary resonant frequencies, respectively;

a high quality factor (Q) FSS having a lower primary resonant frequency relative to said first and second primary resonant frequencies, said high Q FSS interposed between said first and second FSS and having a loaded Q of at least thirty at said lower primary resonant frequency;

a first dielectric layer interposed between said first FSS and said high Q FSS; and

a second dielectric layer interposed between said second FSS and said high Q FSS.

2. The FSS-based device according to claim **1**, wherein said high Q FSS comprises a plurality of dielectric comprising features formed in an electrically conductive layer.

3. The FSS-based device according to claim **2**, wherein said high Q FSS comprises a plurality of slot antennas.

4. The FSS-based device according to claim **3**, wherein said slot antennas comprise a straight slot having a set of balanced spirals disposed at each end of said straight slot.

5. The FSS-based device according to claim **3**, wherein said slot antenna comprises a dual-polarized crossed slot antenna.

6. The FSS-based device according to claim **1**, wherein a thickness of said FSS-based device is $<\lambda/10$, where λ is a wavelength of operation of said FSS-based device.

7. The FSS-based device according to claim **1**, further comprising a plurality of FSS-based devices stacked together by sharing at least one common layer selected from said first and second FSS.

8. The FSS-based device according to claim **1**, wherein said first and second primary resonant frequencies are each at least 1.3 times larger than said lower primary resonant frequency.

9. The FSS-based device according to claim **1**, wherein said first and second primary resonant frequencies are each at least three times larger than said lower primary resonant frequency.

10. A system, comprising:

a propelled object or vehicle; and

a frequency selective surface based (FSS-based) device coupled to said propelled object or vehicle, said FSS-based device configured for processing electromagnetic waves and comprising

a substrate having a surface layer; and

a multi-layer frequency selective surface (FSS) structure disposed on said surface layer, said multi-layer FSS structure comprising a first FSS having a first primary resonant frequency, a second FSS having a second primary resonant frequency, a high quality factor (Q) FSS interposed between said first FSS and said second FSS, a first dielectric layer interposed between said first FSS and said high Q FSS, and a second dielectric layer interposed between said second FSS and said high Q FSS;

wherein said high Q FSS has a lower primary resonant frequency relative to said first and second primary resonant frequencies and a loaded Q of at least thirty at said lower primary resonant frequency.

11. The system according to claim **10**, wherein said high Q FSS comprises a plurality of dialectic comprising features formed in an electrically conductive layer.

12. The system according to claim **11**, wherein said high Q FSS comprises a plurality of slot antennas.

13. The system according to claim **12**, wherein said slot antennas comprise a straight slot having a set of balanced spirals disposed at each end of said straight slot.

14. The system according to claim **12**, wherein said slot antenna comprises a dual-polarized crossed slot antenna.

15. The system according to claim **10**, wherein a thickness of said multi-layer FSS structure is $<\lambda/10$, where λ is a wavelength of operation of said FSS-based device.

16. The system according to claim **10**, wherein said multi-layer FSS structure comprises a plurality of FSS-based devices stacked together by sharing at least one common layer selected from said first and second FSSs.

17. The system according to claim **10**, wherein said first and second primary resonant frequencies are each at least 1.3 times larger than said lower primary resonant frequency.

18. The system according to claim **10**, wherein each of said first and second primary resonant frequencies are each at least three times larger than said lower primary resonant frequency.

19. The system according to claim **10**, wherein said propelled object or vehicle is an aircraft, a missile, or a ship.

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