# A Design Using Double-Deck Nonuniform Transmission Line (NTL) Meshed-Planar Fan-Electromagnetic Bandgap (MP-FEBG) Structure for Ultra-Wideband (UWB) Antenna

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***Abstract*—In this paper, a double layer planar ultra-wideband (UWB) antenna with the meshed-planar electromagnetic bandgap (MP-EBG) structure is proposed. The antenna is composed of a wideband radiation element and a wideband filter realized by nonuniform transmission line (NTL). The structure of the sector is beneficial to the increase of the antenna bandwidth. The double layer structure can greatly reduce the size of the antenna, and the aperture structure can easily adjust antenna's performance. The simulation results show that the antenna can achieve a wide bandwidth from 3.20 to 15.78 GHz with return loss less than -10 dB and exhibit stable antenna gain. It is demonstrated that the measurement agrees with the calculation well and the desired characteristics are obtained.**

***Index Terms*—ultra-wideband (UWB); meshed-planar fan-electromagnetic bandgap (MP-FEBG); antenna**

## I. INTRODUCTION

With development of ultrawideband technology, there is increasing demand for small low-cost antennas with wide frequency bandwidth and omnidirectional radiation patterns. The printed monopole antennas have received great attention in UWB applications due to their advantages of simple structure, low cost, light weight, low profile, easy fabrication, wide impedance bandwidth, and easy integration with other microstrip circuits. With respect to frequency band de fined by the Federal Communications Commission (FCC) for UWB applications, which is from 3.1 to 10.6 GHz [1], several printed monopole antennas with different geometries have been proposed recently [2], [3], [4].

The early works on frequency band-rejected UWB antennas were realized by utilizing small strip bars[5], U-shaped slot[6], an open-loop resonator[7], a pentagonal radiating patch with two bent slots[8], and a half-mode substrate integrated waveguide cavity[9]. According to [5]–[7], however, the elements were developed on the back side of the same layer for generating single and/or dual-frequency band-notched antennas or on the same layer within the antenna radiator. Therefore, due to the space limitation, it is very difficult to generate multiple band notches. On the other hand, in reference to [5] and [6], the designs not only have complicated structures which can lead to high fabrication costs and big antenna size, but have made it difficulty in the integration with microwave integrated circuits. Moreover, the size of some UWB antennas is shown in TableⅠ.

TABLE I. DIMENSIONS OF SOME OF THE EARLIER P UBLISHED ANTENNAS IN COMPARISON TO THE PROPOSED ANTENNA

| Some of the UWB monopole antennas | Size of the antenna (mm$^3$) |
|---|---|
| Slotted planar binomial monopole antenna[10] | 30×27.4×1 |
| Slotted circular monopole antenna[11] | 26×27×1 |
| Conductor-backed plane rectangular antenna[12] | 22×22×1 |
| Rectangular antenna with slotted ground[13] | 35×35×1.6 |
| Fork-shaped antenna[14] | 35×30×0.769 |
| Slotted arc-shaped edge rectangular antenna[15] | 24×35×0.8 |
| Slotted rectangular monopole antenna[16] | 18×20×1 |
| Slitted rectangular monopole antenna[17] | 16×20×1 |
| Proposed antenna in this letter | 0.25π× 1 × 14 × 14 |

In this letter, a new UWB printed monopole antenna with compact size and proper radiation characteristics is presented. And I seek to miniaturize the antenna design through a three-pronged approach, which is of small size, large bandwidth (BW), and low cost. The proposed antenna with a small size of 0.25 ×Π× 1.2 × 14 × 14mm$^3$ using double-deck MP-FEBG on the substrate of FR4 achieves a wide impendence bandwidth from 3.20 to 15.78 GHz with return loss less than -10 dB. Dimensions of the proposed antenna and some of the previously published antennas are presented in Table I for comparison.

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## II. Design Concept

### A. Antenna Radiation Elements Design

In order to use the spectrum of the UWB, the radiation element of the antenna is required to operate over the broad frequency band range from 3.1 to 10.6 GHz. It is also required to that the radiate ommi-directionally for good performance in indoor wireless communication. Planar elliptical, NTL and rectangular shape monopole antennas have been proposed to satisfy the requirements. On the one hand, these shapes have gradual impedance matches at broad frequency for their scalability of the radiation. On the other hand, the radiation by these radiation elements is ommi-directional for their compact size. The radiation elements of the antenna used in this paper has a shape of double-deck MP-FEBG monopole based on this fact.

### B. Filter Design By Inverse Scattering Theory

The antenna we proposed is based on the MP-EBG with nonuniform width. When the desired frequency characteristics of the transmission line are given, the theory of the NTL is determined by solving, Zakharov-Shabat inverse scattering problem [18]-[19].

The equivalent circuit elements of the NTL is shown in Fig. 1, where $z$ represents the position of the transmission line, L and C are the inductance and capacitance per unit length of the transmission line, respectively.

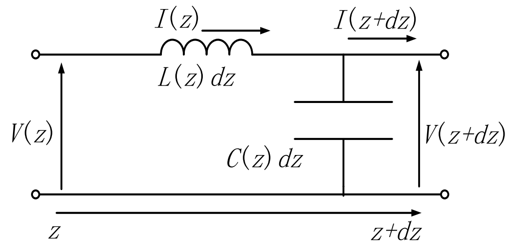



Figure 1. E.quivalent circuit elements of the NTL

The telegrapher's equations for the current $I$ and voltage $V$ with a time factor of exp($-j\omega t$) are shown by

$$\frac{dV(z)}{dz} = j\omega L(z)I(z) \tag{1}$$

$$\frac{dV(z)}{dz} = j\omega C(z)V(z) \tag{2}$$

Finaly, the impedance profile is derived as

$$Z(x) = Z(0)\exp\left(2\int_0^x q(s)ds\right) \tag{3}$$

### C. MP-EBG Structure

In [20], a design which used MP-EBG structure for ultra-wideband system-in-package for suppression of Power/Ground Noise Using is proposed.

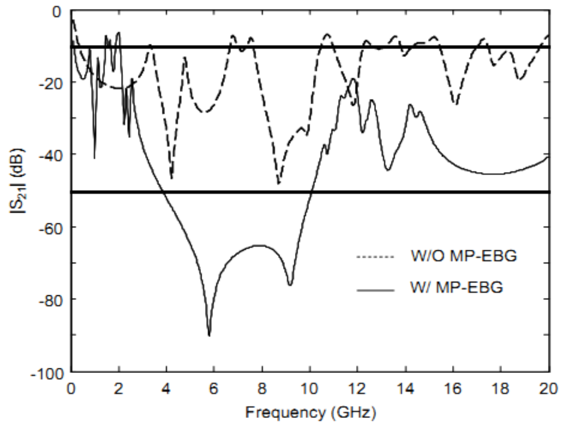



Figure 2. Simulated S-parameter (S21) of PWR/GND planes with and without MP-EBG structure.

In [20], the simulation result from SIwave is presented in Fig. 2. The simulation result is the magnitude of S21 to illustrate the noise stopband. The solid line illustrates the S21 magnitude of PWR/GND planes with MP-EBG structure. The dashed line represents the S21 magnitude of PWR/GND planes without MP-EBG structure as a reference. The figure shows the ultra-wideband stopband characteristic.

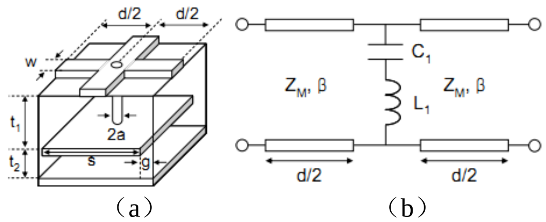



Figure 3. (a) Dimensions of a unit cell of the MP-EBG structure and (b) Transmission-line model for one unit cell to explain the stopband enhancement

The Fig. 3 shows the dimensions of one unit cell structure and the transmission-line model for the MP-EBG structure. To explain the stop bandwidth enhancement of the MP-EBG structure, the transmission-line model for one unit cell [21] is used. The lower layer of thickness $t_1$, containing the rods, has a relative dielectric constant of $\varepsilon r_1$, while the upper layer of thickness $t_2$ has a relative dielectric constant of $\varepsilon r_2$.

It is shown in [22] that a quasi-TEM mode excited within an empty (parallel-plate waveguide) PPW (without patches or vias) of height and width having magnetic sidewalls can be modeled as a simple transmis-sion line whose characteristic impedance and phase constant, respectively, are given by

$$Z_0 = \frac{\eta_0}{\sqrt{\varepsilon_{r,\mathrm{eff}}}}\frac{h}{d}, \beta' = \frac{\omega}{c}\sqrt{\varepsilon_{r,\mathrm{eff}}}, \tag{4}$$

where $\eta_0$ is the wave impedance of free space (377Ω), $c$ is the speed of light in a vacuum, $\omega$ is the radian frequency, and the effective dielectric constant for the $z$-directed electric field is given by

$$\varepsilon_{r,\mathrm{eff}} = \frac{t_1 + t_2}{\dfrac{t_1}{\varepsilon_{r1}} + \dfrac{t_2}{\varepsilon_{r2}}} \tag{5}$$

The presence of the patches and vias is accounted for by a shunt LC branch circuit. The lumped capacitance is approximated by

$$C_1 = \frac{\varepsilon_0 \varepsilon_{r2}(s^2 - \pi a^2)}{t_2} \tag{6}$$

where *ε0* is the permittivity of free space (-8.85×10-12 F/m).

Finally, the effective phase constant *kx* is derived as

$$k_x = \frac{1}{d}\cos^{-1}\left[\cos(\beta d) - \frac{\omega C_1 Z_0}{2(1-\omega^2 L_1 C_1)}\sin(\beta d)\right] \tag{7}$$

The bandwidth of the stopband is predicted by using the equation (17). The equation shows that the bandwidth increases as the characteristic impedance increases. The MP-EBG structure has a wide stopband characteristic since the characteristic impedance $Z_M$ of the MP-EBG structure with the narrow power plane is larger than the impedance of a mushroom-type EBG structure [20].

*D. Concept of Double-Deck NTL MP-FEBG*

The impedance of the exponentially increasing transmission line is given by

$$Z(x) = Z_0 e^{ax} \qquad 0 < z < l \tag{8}$$

from equations (3) and (8), *α* is given by

$$a = \frac{1}{l} 2\int_0^l q(s)ds \tag{9}$$

In [23], the total reflection coefficient of the exponentially increasing transmission line is derived as

$$\Gamma_{in} = \frac{1}{2}\int_{x=0}^{l} e^{-2j\beta x} \frac{d \ln \frac{Z}{Z_0}}{dx} dx \tag{10}$$

Then, in this paper, the total reflection coefficient of the NTL is derived as

$$\begin{aligned}\Gamma_{in} &= \frac{1}{2}\int_0^l e^{-2j\beta x} \frac{d \ln \exp\left(2\int_0^x q(s)ds\right)}{dx} dx \\ &= \frac{1}{2}\exp\left(2\int_0^x q(s)ds\right)\cdot e^{-j\beta l}\cdot\frac{\sin \beta l}{\beta}\end{aligned} \tag{11}$$

when the reflective coefficient at the end is $\Gamma_L$, the minimum length of the NTL is

$$l_{\min} = \frac{1}{4\beta|\Gamma_L|} 2\int_0^x q(s)ds \tag{12}$$

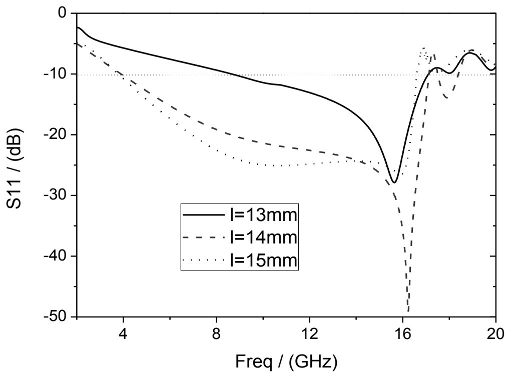



Figure 4. Returns loss for different length l of NTL

In the frequency range of 3.1-10.6 GHz, the minimum length of the NTL is determined to set as 14mm in order to guarantee the reflection coefficient of UWB antennas is less than 10%.

$$s = \sum_{n=1}^{N} s_{2n} - \pi R^2 \qquad s_{2n} = n \cdot r^*(\gamma - \beta)\cdot w \tag{13}$$

where *α*, *β*, *γ*, *R*, *w* is shown in Fig. 6, *n* is the ordinal of vias with radial distribution, r* is radius of the nearest via. In this paper, $C_1$, *d*, $Z_0$, $L_1$, *Y* is derived as

$$C_1 = \frac{\varepsilon_0 \varepsilon_{r1} s}{t_1} \tag{14}$$

$$d = r \cdot \frac{\gamma - \alpha - \beta}{2} \tag{15}$$

$$Z_0 = \frac{\eta_0}{\sqrt{\varepsilon_{\mathrm{r,eff}}}} \frac{2h}{r(\gamma - \alpha - \beta)} \qquad \varepsilon_{\mathrm{r,eff}} = \varepsilon_r \tag{16}$$

$$\nu = \frac{\pi R^2}{d^2} = \frac{4\pi R^2}{r^2}\cdot(\gamma - \alpha - \beta)^2 \tag{17}$$

The lumped inductor can be estimated from [24] as

$$L_1 = \frac{\mu_0 t_1}{4\pi}\left[\ln\left(\frac{1}{\nu}\right) + \nu - 1\right] \tag{18}$$

where *μ0* is the permeability of free space (4π×10-7H/m), and the parameter *ν* is the ratio of the via cross section to the cross section of the entire unit cell. The patch and via present a shunt susceptance given by

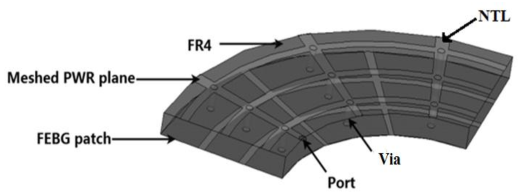
$$Y = \frac{j\omega C_1}{1 - \omega^2 L_1 C_1} \tag{19}$$

Finally, the effective phase constant $k_x$ of the double-deck NTL MP-FEBG is derived as

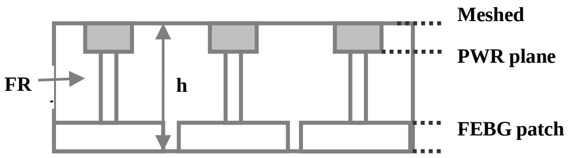
 

$$k_x = \frac{2}{r(\gamma-\alpha-\beta)}\cos^{-1}\left[\begin{array}{l}\cos(\beta' r\cdot\frac{\gamma-\alpha-\beta}{2})-\\ \frac{\omega C_1 Z_0}{2(1-\omega^2 L_1 C_1)}\sin(\beta'\cdot r\cdot\frac{\gamma-\alpha-\beta}{2})\end{array}\right] \tag{20}$$

According to equation (20), EBG leaves much to be desired in terms of involving a stable effective phase constant. Consequently, the structure of nonuniform fan patches in MP-FEBG deserves expectation in order to get a wider band of the antennas.




(a)




(b)

Figure 5. The meshed planar FEBG structure. (a)3D structure of the proposed MP-FEBG structure which provides ultra-wideband antenna.(b) Cross-sectional view on the dashed line of (a)Which contains double layer - a meshed PWR layer and a FEBG patch layer.

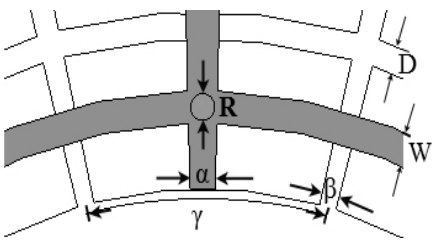



Figure 6. The unit cell of the MP-FEBG structure which provides the dimensions in detail.

Based on the foregoing analysis, on the one hand, the plane fan antenna has frequency bandwidth and small size. Besides its phase center does not vary with frequency. It is suitable for the exposure, or ultra-bandwidth array antenna. On the other hand, the package level MP-FEBG structure can suppress the power/ground noise in the UWB band. The result shows that the MP-FEBG structure has UWB stopband. The meshed power plane with the narrow plane width increases the impedance in a unit cell of the MP-FEBG structure. This enables the stopband to be broadened.

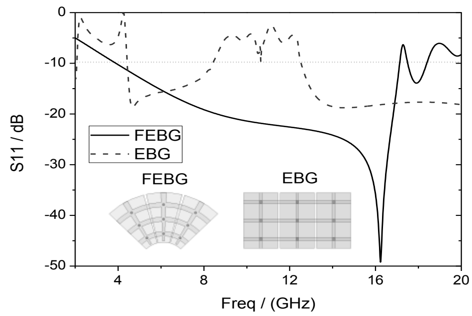



Figure 7. Returns loss for FEBG and EBG

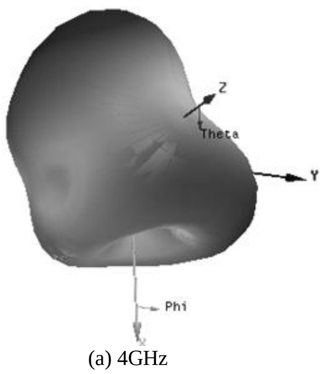
Therefore, in order to achieve the purpose of ultra-wideband, it is necessary to combine the plane fan antenna with the MP-EBG structure.

## III. Establishment of The Antenna Model

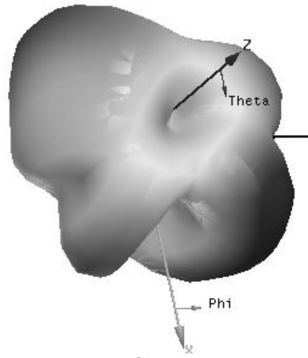
The test structures for the simulation are shown in Fig.5 and Fig. 6. The simulations are performed by using HFSS10.0. The size of the MP-FEBG structure for simulation is $0.25\pi \times 1 \times 14 \times 14 mm^3$.

The meshed PWR plane contains mesh fan-grids consisting of three row curved bars and three column bars, which printed over the top substrate layer. Vias are placed on the cross points of each bar to connect meshed PWR planes with FEBG patches. And the FEBG patch contains mesh fan-grids which consist of three row fan patches and three column fan patches. It is fed by a microstrip feedline, which is printed over the top substrate layer.

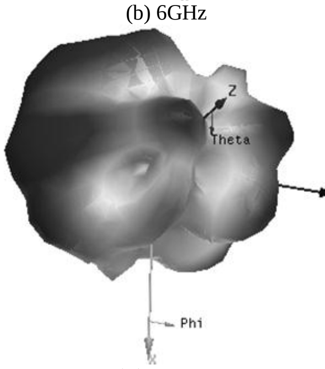
The angle of each bar is 3° and the inside radius is 5.0mm and the outside radius is 14.0mm. Vias are placed on the cross points of each bar to connect meshed PWR planes with FEBG patches. A FEBG patch is a fan plat. The inside radius is 5.6mm and the outside radius is 14.0mm and the angle is 27°.The angle between each FEBG patch is 30°. So the gap distance between EBG patches is 2°. The stack-up of the test structure is shown in Fig. 4 (b). The thickness of each copper layer is 35um. It was fabricated by the standard PCB fabrication process. The dielectric substrate used in the designs was FR4_epoxy with loss tangent of 0.02, dielectric constant of 4.4, and substrate thickness of 1mm.




(a) 4GHz




(b) 6GHz




(C)106GHz

Figure 8. Simulation radiation patterns for the proposed antenna at (a) 4GHz; (b) 6GHz;(C)106GHz

The simulation antenna gains and VSWR for the proposed structures at specific frequencies are shown in Fig. 9. The VSWR is less than 2. The gains are within a range of 1.55-3.35 dBi.

In Fig. 10, it exhibits the comparison of the measured to the simulated $S_{11}$ of the antenna array. It can be observed that the frequency range for $S_{11}$<-10dB is 3.20GHz-15.78GHz. A slight frequency shifting (3% with respect to the center frequency) is observed, which may be caused by the tolerance of fabrication and the fluctuation of permittivity.

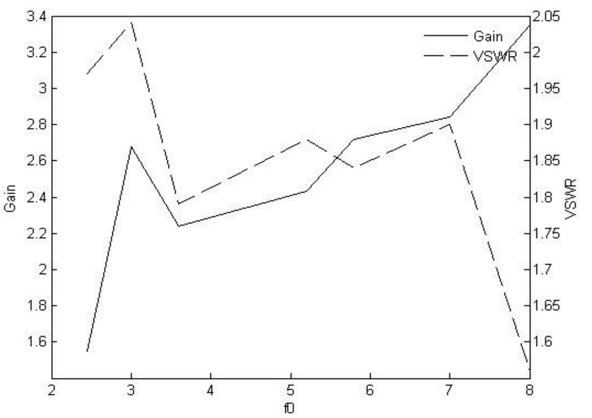



Figure 9. Simulation result of the gain and VSWR of the antenna

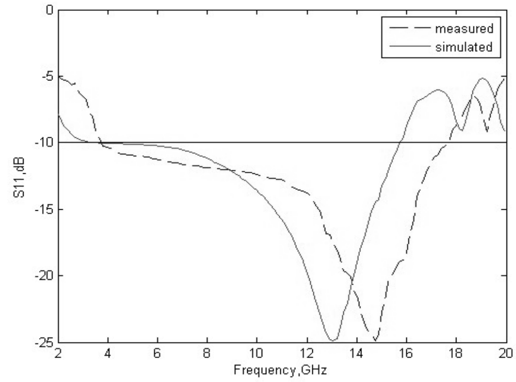



Figure 10. Simulation result of the return loss

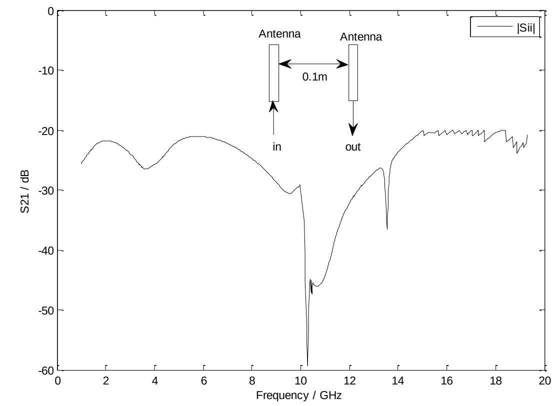



Figure 11. Measured magnitude of transfer function

Fig. 11 and Fig. 12 exhibit the magnitude and group delay of the antenna system transfer function of a double-deck fan-electromagnetic bandgap antenna pair which is composed of two identical double-deck fan-electromagnetic bandgap antenna prototypes and positioned face to face with a separation of 0.1meter. It can be seen that the variation of the group delay is almost within 1ns across the working band. It confirms that the proposed antenna exhibits phase linearity at desired UWB frequencies.

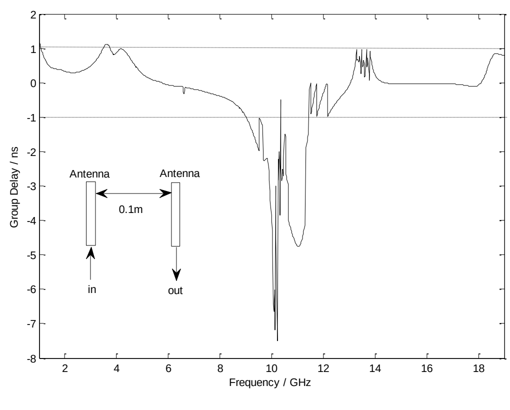



Figure 12. Measured group delay

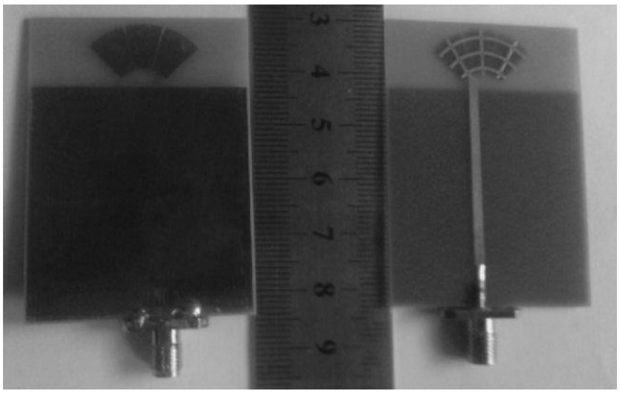


Figure 13. The photograph of the antenna array prototype

The simulated results show that the antenna achieves a wide impendence bandwidth from 3.20 to 15.78 GHz with return loss less than -10 dB. The bandwidth has been completely covered the frequency band 3.1–10.6 GHz, which is released by the FCC.

## IV. Conclusions

A MP-FEBG UWB antenna with the NTL filter designed by solving Zakharov-Shabat inverse scattering problem has been presented. Comparing to the regular patch antenna, the proposed antenna size has been successfully reduced and the bandwidth has been greatly increased. In addition, due to the small size of the antenna, the antenna's performance may be affected by the changes of the various parameters.

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