Miniaturization of Patch Antenna through Metamaterial Approach

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***Abstract*— This paper is focusing on investigating a method of reducing size through metamaterial approach for Wi-Fi application. A patch antenna has been designed as a prototype to measure the performance. The antenna resonates at 2.45 GHz. Metamaterial characteristics exhibits negative permittivity and permeability after introducing DGS structures by Nicolson-Ross-Weir (NRW) equations. A Simulation has been carried out using Computer Simulation Technology Microwave Studio (CST-MWS). A Vector Network Analyzer (VNA) was used to measure return loss, S11. The antenna was fabricated on Rogers RO3003 substrate with permittivity, εr=3.00 and thickness, h=0.75mm. The simulation and measurement results show that the metamaterial antenna improves the return loss S_{11} and size of the antenna reduces by 38.23% and 82.77% respectively compare to the conventional antenna.**

***Index Terms*— Metamaterial, rectangular patch antenna, rectangular DGS and return loss.**

I. INTRODUCTION

Recently microstrip patch antennas are widely used in satellite communications, aerospace, radars and biomedical applications because of its inherent characteristics such as light weight, low profile, low cost, mechanically robust, compatibility with integrated circuits and very versatile in terms of resonant frequency, polarization, radiation pattern and matching impedance. Microstrip antennas however face few weaknesses in terms of narrow bandwidth, low efficiency and relatively large size [1]-[2].

There are many kind of materials were used to improve the performances of microstrip patch antenna. Among them, metamaterials are found to be most suitable [3]. Metamaterials are also known as Left-Handed Metamaterial (LHM) where the permeability and permittivity were simultaneously negative [4]. Negative permittivity means that the materials are physically unique, have unusual realizable response functions and may not be easily found in nature [5].

The use of the metamaterials is to improve some basic antenna features such as impedance matching, gain, bandwidth, efficiency, which has represented a novel way of overcoming the limitations shown by some of the well-known techniques for reducing the antenna size [6]. Metamaterial antennas open a way to overcome the bandwidth limitation in small antennas [7].

Many methods are used to reduce the size of Metamaterial Patch Antenna (MPA) like using Planar Invert-F Antenna structure (PIFA) or using substrate with high dielectric constant [8]. Defect Ground Structure (DGS) is one of the methods that can be used to reduce the antenna size.

DGS also acts as a Perfect Magnetic Conductor (PMC) at a certain frequency band, and reflects the electromagnetic waves with a near zero degree reflection phase. So placing an DGS structure underneath a radiating element will reflect the electromagnetic wave back in phase, and reduce the backward radiation [11].

The evolution of DGS is from the Electron Band Gap (EBG) structure [9]. The substrate with DGS must be design so that it becoming metamaterial. The substrate with DGS is considered as metamaterial substrate when both relative permittivity, εr and permeability, μr negative Referring to [15], the design, simulation and fabrication of a Left-Handed Metamaterial (LHM) structure are presented. The project used the combination of the modified square rectangular Split Ring Resonator (SRR) and the Capacitance Loaded Strip (CLS) to obtain the negative value of permeability, μ and the negative permittivity, ε. Nicolson Ross-Wier approach was used to identify the double negative region. However, this project was unable to reduce the side and back lobe. The gain of the microstrip antenna with LHM structure could be further improved if the side and back lobe can be reduced.

Reviewing on the literature, this project proposed a design of a rectangular metamaterial patch antenna with DGS structure operating at frequency of 2.45GHz. The rectangular metamaterial patch antenna with DGS structure should be able to maintain a good return loss, VSWR, gain, and bandwidth compared to the microstrip patch antenna without DGS structure.

II. METHODOLOGY

The approached of this design is represented in the flow chart in Fig. 1.

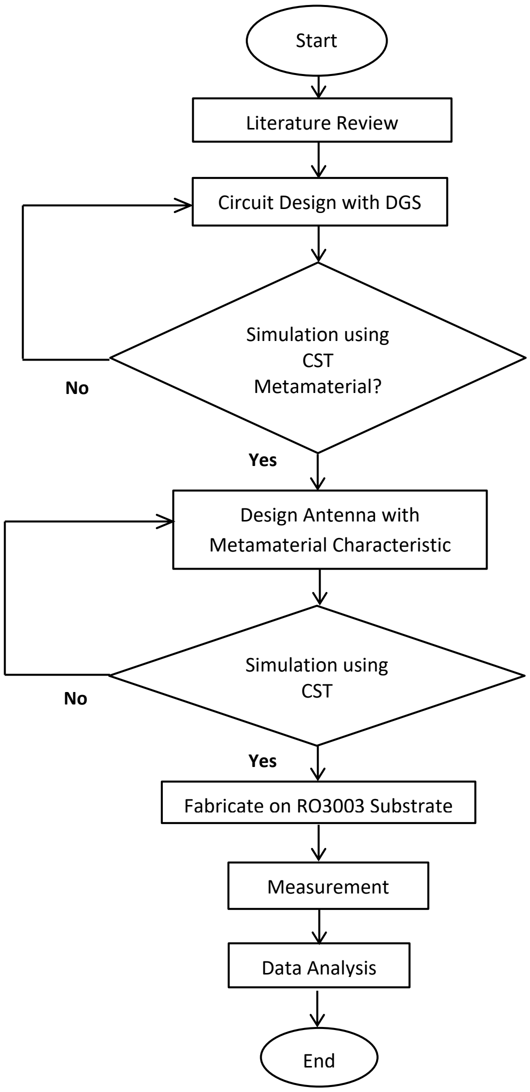


Fig. 1. Flow chart of the project design.

CST Microwave Studio software is used for designing and simulating the antenna design. The microstrip antenna with DGS structure was implemented to find the metamaterial response of the substrate that having both permittivity, ε_r and permeability, μ_r were negative. The metamaterial characteristics were verified using Nicolson-Ross-Weir (NRW) method.

A. *Microstrip patch antenna with DGS substrate*

Rectangular microstrip patch antenna is fabricated on Rogers RO3003 substrate with DGS structures at the ground plane to resonate at 2.45 GHz. The cross-sectional view is shown in Fig 2.

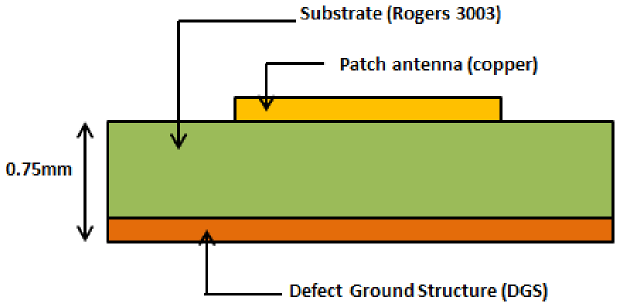


Fig. 2. A cross-sectional view : Rectangular microstrip patch antenna

These structures were designed based on [14]. Characteristics of Rogers RO3003 substrate is tabulated in Table I.

TABLE I
ROGERS RO3003 SUBSTRATES CHARACTERISTICS

Characteristics	**Values**
Permittivity	3.00
Permeability	1.00
Thickness	0.75 mm
Copper cladding	0.035 mm

B. *DGS Structures Design*

The DGS structure with split ring is designed on the ground plane of the Rodgers RO3003 substrate by using equation below:

$$\frac{\lambda g}{2} = \frac{c}{2f\sqrt{\varepsilon r}} \qquad (1)$$

The geometry of the square DGS structure is shown in Fig.3.

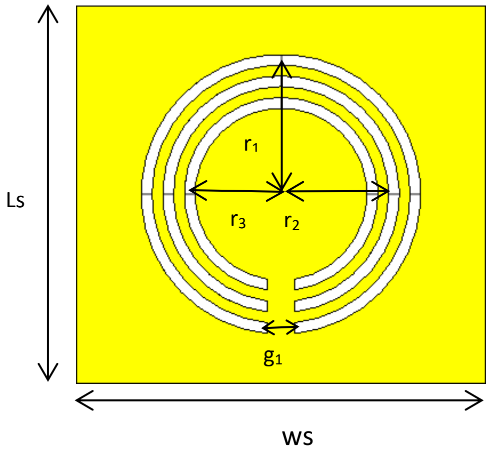


Fig. 3. View of DGS structure

The dimensions of DGS structure and substrate are tabulated in Table II.

TABLE II
DIMENSION OF DGS STRUCTURE AND SUBSTRATE

Parameters	Values (mm)
ws	36
Ls	36
g_1	2.24
r_1	6
r_2	5
r_3	4

Fig. 3 shows three rings with different inner radius of 4mm, 5mm and 6mm. The thickness of the split ring is 0.5mm respectively. The ring have 2.24mm split gap, g1.

The metamaterial features with negative permittivity and permeability occurs at frequency of 2.45 GHz. Both permeability and permittivity is obtained from S-parameter using Nicholson-Ross-Weir (NRW) technique. The method is as follows :

$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{2}$$

$$X = \frac{s_{11}^2 - s_{21}^2 + 1}{2s_{11}} \tag{3}$$

$$\mathrm{T} = \frac{s_{11} + s_{21} - \Gamma}{1 - (s_{11} + s_{21})\Gamma}\,. \tag{4}$$

Where;

Γ = reflection coefficient of the circuit
X = correct root
T = transmission coefficient
S_{11} = reflected signal
S_{21} = transmitted signal

Both values of S_{11} and S_{21} were obtained from CST-MW. The magnitude value of the reflection coefficient, Γ must be less than one (Γ<1) in order to find the correct root (X) in form of S-parameters. Calculation for T of the metamaterial is as follows;

$$\ln\left(\frac{1}{\mathrm{T}}\right) = \ln\left(\frac{1}{\mathrm{T}}\right) + j(\theta_{\mathrm{T}} + 2\pi n) \tag{5}$$

$$n = \frac{L}{\lambda_g} \tag{6}$$

Where;

n = number of roots (0, ±1, ±2,…)
L = material length
λ_g = wavelength in sample
θ_T = phase of transmission coefficient in radian

The number of roots which is the value of n must be rounded up to the nearest integer to get the actual root number. This value can be determined using equations (7) and (8) along with substituting the value from equation (8) into equation (6).

$$\frac{1}{\Lambda} = -\frac{1}{\lambda_o}\sqrt{\varepsilon_r^o \mu_r^o - \left(\frac{\lambda_o}{\lambda_c}\right)^2} \tag{7}$$

$$\left(\frac{1}{\Lambda}\right) = \frac{1}{\lambda_g} \tag{8}$$

Where;
Λ = complex number of wavelength
ε_r = initial guess of material permittivity
μ_r = initial guess of permeability
λ_0 = wavelength in free space
λ_c = cut-off wavelength

Value from equation (5) is substituted into equation (9).

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2 \tag{9}$$

Equation for permeability, μ_r and permittivity, ε_r are as follows;

$$\mu_r = \frac{1 + \Gamma}{(1 - \Gamma)\Lambda\sqrt{\frac{1}{\lambda_o^2} - \frac{1}{\lambda_c^2}}} \tag{10}$$

$$\varepsilon_r = \frac{\lambda_o^2}{\mu_r}\left[\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2\right] \tag{11}$$

All these formulas were program in Microsoft Excel to obtain a plot of permittivity value of metamaterial versus frequency.

C. Conventional Microstrip Patch Antenna

A conventional patch antenna was designed in order to ma a comparison in term of the performance and size to the metamaterial antenna. The conventional patch antenna equations were taken from [12] and [13]. Dimension of the microstrip patch antenna have been calculated using equation (12)-(17);

i) Width dimension, W

$$W = \frac{c}{2f\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{12}$$

ii) Effective dielectric constant, ε_{reff}

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} \qquad (13)$$

iii) Extension length, ΔL

$$\Delta L = 0.412\,h\,\frac{(\varepsilon_{reff} + 0.3)\left(\frac{w}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{w}{h} + 0.8\right)} \qquad (14)$$

iv) Patch length, L

$$L = \frac{c}{2f\sqrt{\varepsilon_{reff}}} - 2\Delta L \qquad (15)$$

v) Inset feed, y

$$y = \frac{10^{-4}L}{2}\left(\begin{array}{l} 0.001699\,\varepsilon_r^{7} + 0.13761\,\varepsilon_r^{6} - \\ 6.1783\,\varepsilon_r^{5} + 93.187\,\varepsilon_r^{4} - \\ 682.69\,\varepsilon_r^{3} + 2561.9\,\varepsilon_r^{2} - \\ 4043\,\varepsilon_r^{1} + 6697 \end{array}\right) \qquad (16)$$

vi) Ground substrate, Ls

$$Ls = L + 6h \qquad Ws = W + 6h \qquad (17)$$

Dimension of 2.45GHz metamaterial antenna and conventional were shown in Fig 4 and Fig5 respectively:

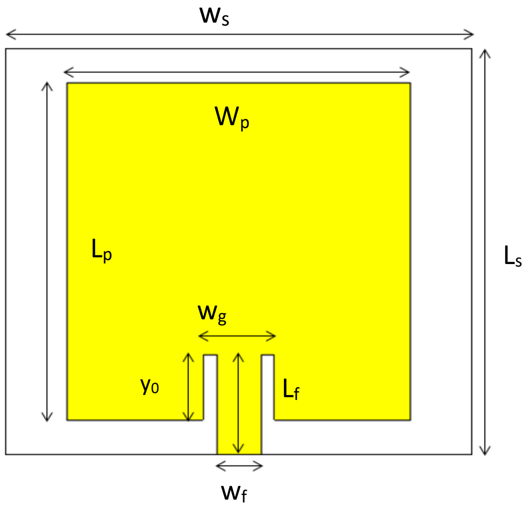


Fig. 4. Metamaterial patch antenna

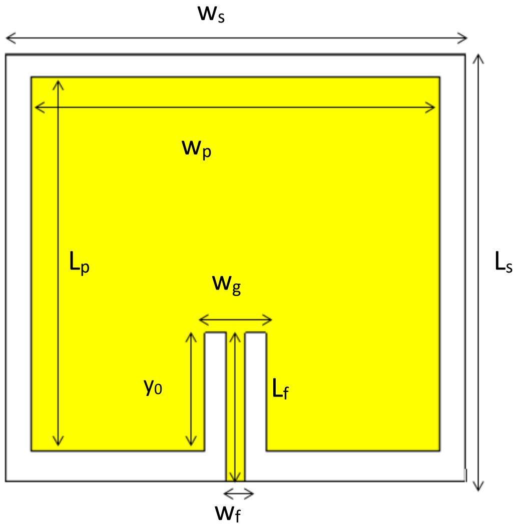


Fig. 5. Conventional patch antenna

TABLE III
DIMENSION OF THE CONVENTIONAL AND METAMATERIAL ANTENNA

Parameters	**Convensional (mm)**	**Metamaterial (mm)**
W_s	44	19
L_s	39.65	17.55
W_p	39	14
L_p	34	14.55
y_0	11	2.8
L_f	13.825	4.3
W_f	1.78	1.8
W_g	5.8	2.9

III. RESULT AND DISCUSSION

The performance of both antennas was investigated through simulation and measurement. The simulation results were obtained from the CST-MW whereas the measurement results were obtained from Vector Network Analyzer (VNA). All results have been recorded and analyzed in order to obtain a clear performance comparison.

A. Simulation Results

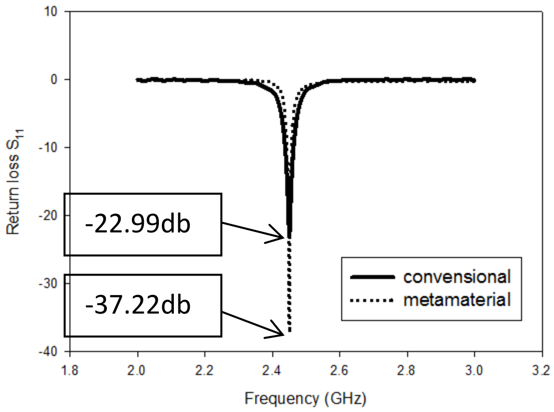
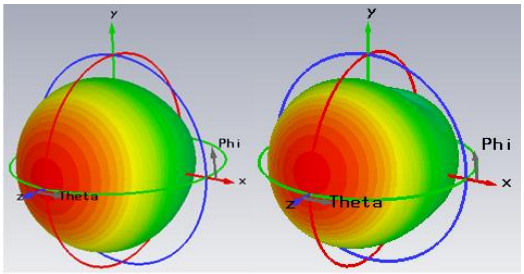


Fig. 6. Simulation result of return loss (S_{11}) for both metamaterial and conventional antennas.

Fig. 6. shows the simulation results of S_{11} for both metamaterial and conventional antennas. S_{11} for metamaterial structure is -37.22 dB while for the conventional antenna is -22.99dB. This simulation result prove that the metamaterial structure improve the return.



a) b)

Fig. 7. 3D plot of antenna directivity in dBi; a) conventional b) metamaterial.

Fig. 7 a) and b) represent 3D plot of the antenna directivity for both conventional and metamaterial respectively. From both figures, the metamaterial antenna produced a slightly lower directivity of 5.181dB compared to the conventional antenna with 5.93dB which is about 13.37% different. The conventional antenna produced a better directivity and wider bandwidth compared to the metamaterial antenna.

TABLE IV

COMPARISON BETWEEN SIMULATION PERFORMANCE OF METAMATERIAL AND CONVENTIONAL ANTENNA

	Metamaterial	**Conventional**	**Difference (%)**
Return Loss, S_{11} (dB)	-37.22	-22.99	38.23
BW (MHz)	14.2	25.4	44.09
Patch Area(mm)	14 x 14.55	39 x 34	84.63
Directivity (dBi)	5.181	5.93	13.37

Comparison between simulation performance of patch antenna for conventional and metamaterial is depicted in table IV. The metamaterial antenna produced a better performance compared to the conventional antenna in term of return loss and area size. The table shows the S_{11} for antenna with DGS improved by 38.23 %. It is proved that the metamaterial would reduce the antenna size. As a result of using DGS, the size of rectangular patch antenna can be reduced up to 84.63 %.

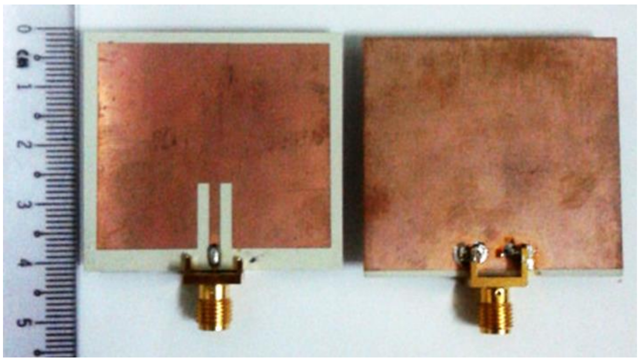
B. Measurement Results

Fig. 8 shows the metamaterial antenna. Fig. 8 a) shows the view of rectangular patch antenna placed at the front of the substrate while fig. 9 b) shows the split ring shaped of DGS structure at the ground plane.

a) b)

Fig. 9. Metamaterial antenna : a) Top b) Bottom views

Fig. 10 represents the view of rectangular patch antenna without DGS structures. Fig. 10 a) and b) shows the top view of the antenna and the bottom view respectively.



a) b)

Fig. 10. Conventional antenna : a) Top b) Bottom view

Patch antenna in Fig. 9 is much smaller than patch antenna in Fig. 10. From the dimension of the antennas, it shows that the DGS compress the antenna size.

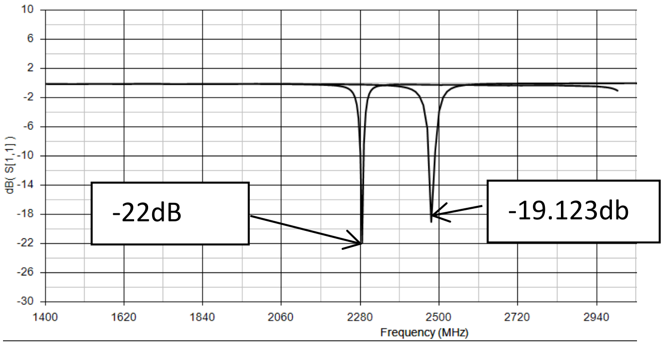


Fig. 11. Measurement result of return loss S_{11} for convensional and metamaterial antennas

Fig. 11. Represents the measurement result of return loss for convensional and metamaterial antenna. The resonant frequency of the antennas are slightly different. The metamaterial antenna resonate at 2.285 GHz which is shifted to the left by 165 MHz while the conventional patch antenna resonates at 2.478 GHz which is shifted to the right by 28 MHz. The differences between these two readings may due to disturbance or interference that affects the circuit in an open air environment. It is also occurs due

to corrosion of copper during fabrication process. However, both antennas produce good return loss, S_{11}. The return loss of metamaterial antenna is -22dB while conventional is -19.123dB. The return loss values for simulated and measured result are significantly differ due to losses in the measurement equipment such as losses due to additional connector and solder lead.

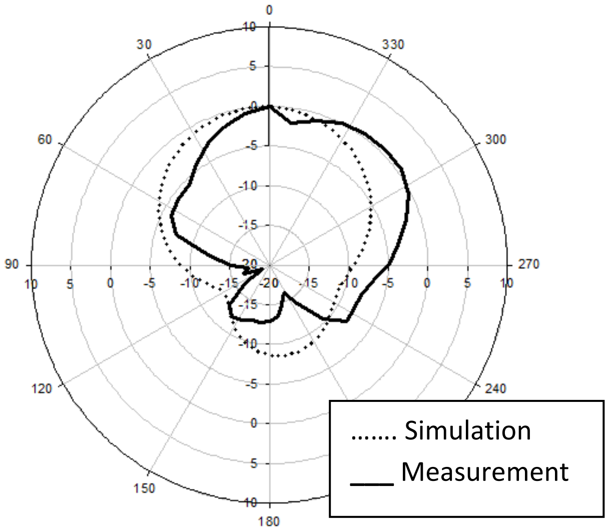


Fig.12 : Radiation pattern for conversional antenna

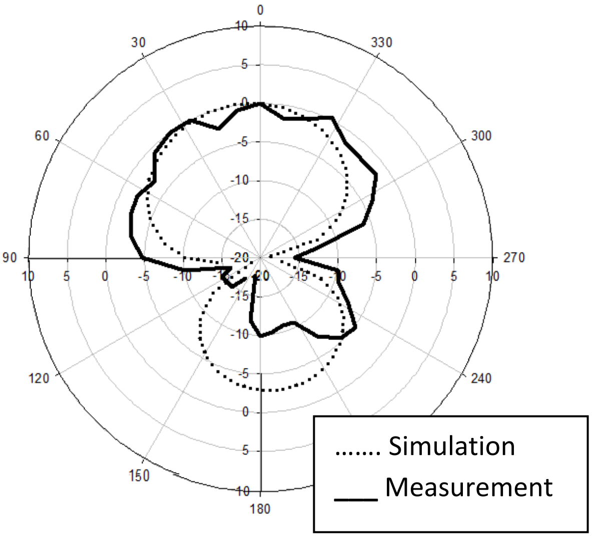


Fig.13: Radiation pattern for metamaterial antenna

Fig. 12 and Fig.13 show the radiation pattern from simulation and measurement for conventional and metamaterial antennas respectively. The radiation pattern from measurement for both antennas is significantly differ due to the environment effect during measurement such as disturbance or interference that affects the circuit in an open air environment.

IV. CONCLUSION

This paper, has demonstrated the rectangular metamaterial antenna with DGS structure. The objective of this project has been achieved to reduce the size of the antenna through metamaterial approach. The presented concept has been successfully simulated, fabricated and measured. The experimental results show a good settlement between the theoretical and measurement results. The size reduction for the proposed metamaterial antenna was able to reduce up to 82.77% compare to the conventional antenna.

V. FUTURE DEVELOPMENT

Future research should investigate on how to increase the directivity of the antenna. The DGS structure might be designed using different shape and dimensions. Other alternative might be different type of antenna such as dipole or array antenna. The DGS structure also can be become a reflector instead of a ground plane such as in this project. To improve the result, the measurement should be done in anechoic chamber. The room is completely absorb reflections of either sound or electromagnetic waves.

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