

# EFFICIENCY IMPROVEMENT FOR QUARTER-WAVELENGTH GROUND-PLANE MONOPOLE ANTENNA BY USING COAXIAL-LOOP WIRE MEDIUM (CLWM)

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## Abstract

The Narrow Band Internet of Thing (NB-IoT) system needs the high-gain omnidirectional antenna since it can efficiently transceiver the signal to/from IoT devices that surrounded itself. Therefore, this paper presents the method for increasing the gain of primary quarter-wavelength monopole antenna using the structure technique of metamaterial, which yields the exact omnidirectional pattern as we required. The metamaterial structure, which we so-called coaxial-loop wire medium (CLWM), consists of a monopole antenna surrounded by multi-turn of small conducting wire loops, surrounded by an air layer and surrounded by multi-turn of larger conducting wire loops. Therefore, the term coaxial loop comes from the inner and outer wire loops sharing a geometric axis. The proposed CLWM was verified that be metamaterial by using the simulated results ( $S_{11}$  and  $S_{21}$ ) from CST software and then compared to the measured results. After that, the permeability, permittivity, and refraction index near zero are calculated by using Nicholson-Ross-Weir (NRW) method, respectively. Finally, we found that the CLWM operates with a monopole antenna can provide the omnidirectional pattern on the azimuthal plane, whereas, in the elevation pattern, its beam width is reduced, causing the realized gain of the conventional monopole is increased around 3.43 dB.

**Keywords:** Gain improvement, wire medium, monopole antenna, omnidirectional pattern, metamaterials

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## Introduction

Narrowband Internet of Things (NB-IoT) is a Low Power Wide Area Network (LPWAN) radio technology standard developed by 3GPP to enable a wide range of cellular devices and services in 2016. (Svetlana, 2016) Later, The GSMA Mobile for Development Foundation, Inc. announced the Extended Coverage GSM IoT (EC-GSM-IoT), which is a standard-based Low Power Wide Area technology. It is based on GPRS and designed as a high capacity, more extensive coverage range, lower energy consumption, low complexity cellular system, and allowing the creation of large groups of stations or sensors that cooperate to share signals for IoT communications. The EC-GSM-IoT network trials have begun, with the first commercial launches planned for 2017. Supported by all major mobile equipment, chipset, and module manufacturers, EC-GSM-IoT networks co-exist with 2G, 3G, and 4G cellular networks as a subset of the LTE standard, but limits the bandwidth to a single narrow-band of 200 kHz. (EC-GSM-IoT, 2016), (Stephen, 2015) For supporting the concept of the IoT, a wireless networking standard of IEEE 802.11ah, which is published in 2017 (IEEE Computer Society, 2016), has been used to be protocol of NB-IoT. It uses 900 MHz, license-exempt bands, to provide extended range Wi-Fi networks, compared to conventional Wi-Fi networks operating in the 2.4 GHz and 5 GHz bands.

There is a prediction that in 2025, there will be more than 75 billion devices connected to IoT. Therefore, the demand for supporting wireless networks is rising. However, to support the more full coverage areas that are a part of the IoT concept, the appropriated antenna for such the IoT network is proposed. In this paper, we offer the improved performance for the primary monopole antenna that easy to fabricate and provide the omnidirectional pattern in azimuth plane by using the structure technique of metamaterial placing surround a monopole antenna.

The monopole antenna sometimes called the Marconi antenna was invented in 1895 and patented 1896 by radio pioneer Guglielmo

Marconi. This antenna type is a resonant antenna oscillating with standing waves of voltage and current along its length, which the wavelength of the radio waves determines its length. The most common form is the quarter-wave monopole, in which the antenna is approximately one-quarter of the wavelength of the radio waves. (Wong, 2012) (Marconi, 1897). Although the monopole antenna provides the actual omnidirectional pattern, it still provides the low gain. Our proposition is how to increase the gain of the monopole antenna, whereas it still provides the omnidirectional pattern.

The gain of monopole antenna can be increased by using the favour methods, namely, the length increment and array. However, the antenna length increases, even though the directivity also increases with length but not enough as we required. Besides, if the length of monopole increases beyond one wavelength ( $l > \lambda$ ), the number of lobes begin to increase. Besides, the directivity improvement of the monopole antenna without increasing the length of the single element, the multi-elements of monopole may be formed to be circular array. However, even though this array type can provide a pattern similar to the original monopole pattern, but the number of lobes still be increased (Balanis, 2005). Therefore, in this paper, the circular-loop wire medium is proposed to increase the gain of the monopole antenna and retain the feature of the omnidirectional pattern.

Generally, the monopole length is calculated from the wavelength of the operating frequency according to the equation

$$\text{of } \lambda = \frac{c}{f_r \sqrt{\mu_{\text{eff}} \times \epsilon_{\text{eff}}}}, \text{ However, we can reduce}$$

the physical size of the antenna by increasing the effective permeability and effective permittivity, which surround the structure. We can observe that when two such parameters are equals, then the antenna length equals the wavelength in free space.

Therefore, this paper presents the method to increase the gain of monopole antenna with

Coaxial-Loop Wire Medium (CLWM) that without any phasing line. Furthermore, the CLWM structure provides no sidelobes, while the obtained main lobe still be retained to appear on the broadside of the monopole axis. In this paper, the radii of two loops of the CLWM structure and gap spacing between the adjacent loops are calculated and optimized the proper values of the effective permeability and effective permittivity of CLWM metamaterials by using the technique of Nicolson Ross Weir and using CST-Microwave studio software for calculation at the frequency band of 920 MHz - 925 MHz for the NB-IoT system.

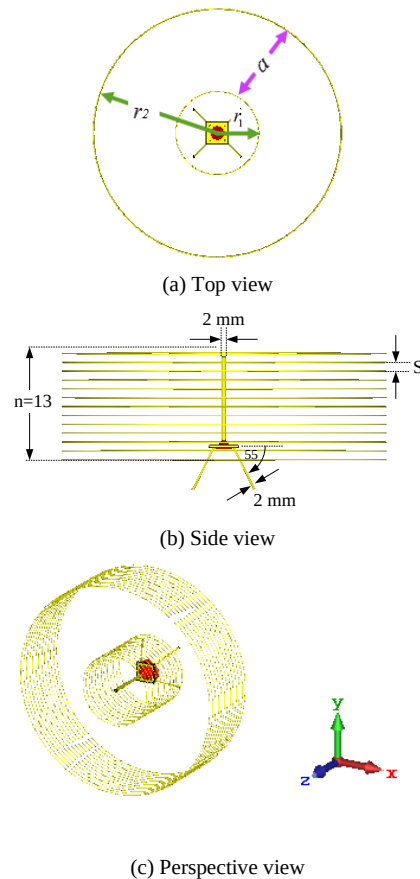
## Theory and Configurations

### Monopole Antenna Covered with CLWM and Simulation

From the image theory of ordinary dipole antenna, a monopole antenna can be visualized as being formed by replacing the bottom half of a vertical dipole antenna with a conducting plane (ground plane) at right-angles to the remaining half. The radiation pattern of the monopole antenna can be calculated by using this image theory. When the ground plane is large enough, the radio waves from the monopole (upper half above ground plane) reflected from the ground plane forming the missing half of the dipole. Thus, the radiation patterns of the monopole and dipole are similar. Whereas the radiation resistance of monopole antenna is half of the dipole antenna and the radiated power of monopole antenna is double of a dipole antenna, causing monopole antenna provides a gain of twice (3 dB greater than) the gain of a similar dipole antenna and HPBW is half of the dipole antenna if it is mounted above a good ground plane.

Whereas, the structure of CLWM consists of two circular rings that have a different radius made from aluminium wires with 1 mm of diameter ( $d$ ). The radii of the inner and outer rings are  $r_1$  and  $r_2$ , respectively, as shown in Figure 1(a). A quarter-wavelength monopole antenna is made from the copper wire with 2 mm of diameter and 7.82 cm ( $0.24\lambda$ ) of the length, and four-radials ground plane

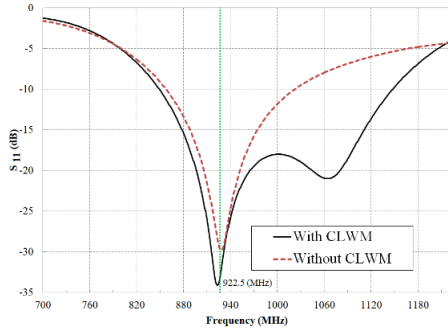
with 4.9 cm ( $0.15\lambda$ ) of the length is inserted at the centre point inside the inner ring, as shown in Figures 1(b) and 1(c). Besides, the four-radials ground plane of the monopole is down at an angle of  $55^\circ$  to increase the input impedance of monopole to around  $50\ \Omega$ , while at the same time lowering the radiation angle more towards the horizon. In order to optimize the dimension of the proper CLWM for a monopole antenna, firstly, the parameters  $r_1$ ,  $r_2$ , the number of inner/outer circular loops ( $n$ ), and the spacing ( $s$ ) between the adjacent loops are adjusted.



**Figure 1. Proposed antenna geometry**

From the simulated  $S_{11}$  in Figure 2, we found that the proposed antenna can provide the excellent impedance matching at 922.50 MHz of the desired frequency when  $r_1$ ,  $r_2$ ,

$s$ , and  $n$  equal to  $0.15\lambda$  ( $\sim 4.9$  cm),  $0.45\lambda$  ( $\sim 14.6$  cm),  $0.025\lambda$  ( $\sim 0.8$  cm), and 13 turns, respectively. Furthermore, it is shown that it can provide a wider bandwidth ( $\sim 301.2$

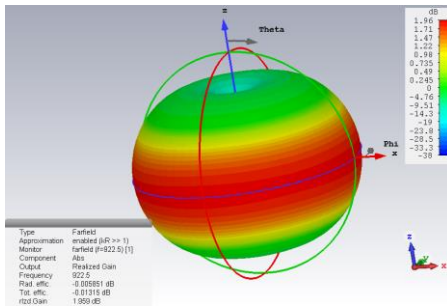


**Figure 2. Simulated  $S_{11}$  of the proposed antenna after the dimension of CLWM is optimized and compared to the simulated  $S_{11}$  of a single monopole**

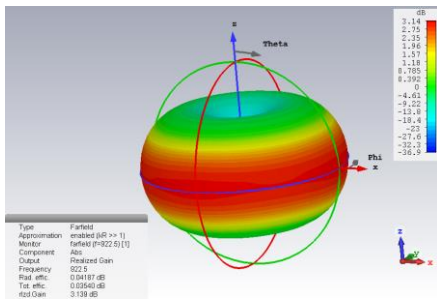
MHz@ $S_{11} = -10$  dB) when compared to the obtained bandwidth from a single monopole ( $\sim 166.86$  MHz@ $S_{11} = -10$  dB).

From the comparative simulated 3-D radiation pattern in Figures 3(a) and 3(b), we found that a monopole antenna with CLWM not only provides the higher gain but also provides higher radiation efficiency ( $e_{cd} = 0.03540$  dB) than the efficiency of a single monopole ( $e_{cd} = -0.01315$  dB). Furthermore, it can yield the exact omnidirectional pattern as we required, as illustrated in Figure 4. Moreover, the co- and cross-polarizations of monopole antenna with CLWM are also considered. We found that the magnitude of power patterns for the resonant frequency of 922.5 MHz at  $\theta = 90$  degrees provided the cross-polarization higher than 150 dB, as shown in Figure 5. Thus the proposed antenna structure provides only vertical polarization.

Besides, we also investigated the length of a single monopole ground plane antenna

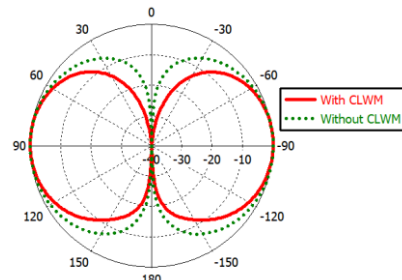


(a) Monopole antenna without CLWM

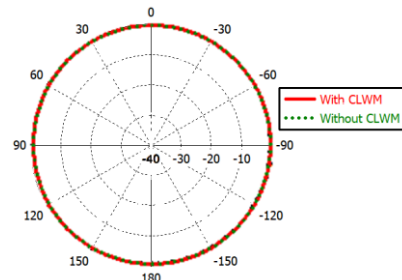


(b) Monopole antenna with CLWM

**Figure 3. Simulated 3-D radiation patterns of (1) monopole antenna without CLWM and (2) monopole antenna with CLWM**

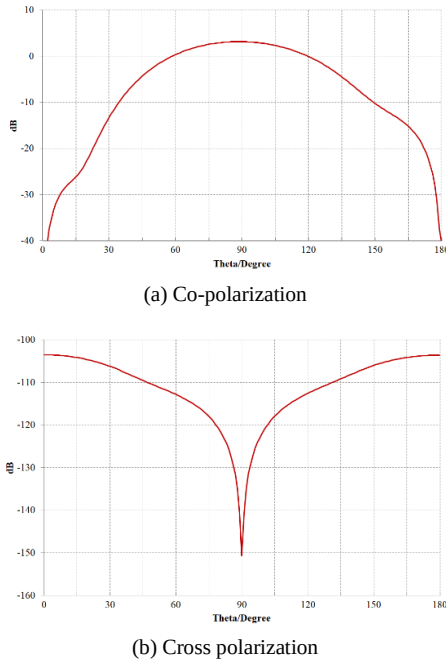


(a) E-plane



(b) H-plane

**Figure 4. Simulated 2-D radiation patterns of a monopole antenna without CLWM compared to a monopole antenna with CLWM**



**Figure 5. Co and Cross Polarization of monopole antenna with CLWM**

without CLMW that can provide the gain near to 3.139 dB at 922.5 MHz, which obtained from our proposed structure, as illustrated in Figure 3(b). From the simulation, it is found that the length of a single monopole antenna is around 19.33 cm ( $0.595 \lambda$ ), it can provide the gain around 3.147 dB. However, we found that the input impedance of this monopole is rather high since the current distribution at feed point close to zero. Even though some matching transformers can be utilized for matching input impedance close to  $50 \Omega$ , but power loss in the transformer will also be increased. Moreover, the radiation angle is directed to the sky instead of towards the horizon.

After the proposed antenna structure was optimized as abovementioned, the electromagnetic waves from monopole antenna can radiate pass through the CLWM structure, efficiently, since the vector of electric intensities of monopole and CLWM have the same direction and matching perfectly. Secondly, the wavenumber of waves ( $k_{clwm}$ ) that travel through CLWM will be

investigated to find the frequency-dependent permittivity of CLWM structure in the next step.

From literature review, Pendry and research team proposed a mechanism for depression of plasma frequency into the far-infrared passing through the periodic structures built of very thin wires (Pendry *et al.*, 1996). After that, Capolino had mentioned about effective medium model and strong spatial dispersion in wire media, which consists of an array of parallel conducting thin wire (Capolino, 2009) by referring the most generally used formula for the plasma frequency that was proposed by Pendry but it is in term of the plasma wavenumber ( $k_{plasma}$ ). In this paper, we have modified such the formula for our CLWM structure. It can write that

$$k_{plasma}^2 = \frac{2\pi}{as \ln\left(\frac{a}{d}\right)} \quad (1)$$

where  $a$  represents the distance of the annular spacing ( $r_2 - r_1$ ) that equals to  $0.3\lambda$  ( $\sim 9.8$  cm) and  $d$  is the diameter of aluminum wire.

However, since our structure consists of multi-coaxial loops, therefore, the relation between annular spacing ( $a$ ) and spacing between the adjacent loops ( $s$ ) must be taken into account. Belov was reported the dispersion of dense grid using the Taylor expansion of sin and cos functions of small arguments to analyse the wavenumber as a function of the lattice constants or spacing between adjacent wires (Ari *et al.*, 2002). Here, we introduce instead of the lattice parameters  $a$  and  $s$ , their product equals to  $\sqrt{as}$ , and their ratio is  $a/s$ , we can write the equation for wavenumber ( $k_{clwm}$ ) of CLWM structure as

$$k_{clwm}^2 = \frac{2\pi}{as \left( \ln \frac{\sqrt{as}}{2\pi d} + F(a/s) \right)} \quad (2)$$

where  $F(a/s)$  in (2) represents the function of a ratio of the distance of annular spacing and spacing between the adjacent loops, as expressed in (3).

$$F(a/s) = -\frac{1}{2} \log\left(\frac{a}{s}\right) + \sum_{m=1}^{\infty} \frac{1}{m} \left( \coth\left(\pi m \frac{a}{s}\right) - 1 \right) + \frac{\pi}{1.8785} \left(\frac{a}{s}\right) \quad (3)$$

From (3), substituting the optimized parameters of CLWM structure into (3), then, we found that the value of  $k_{clwm}$  is the most appropriate for the desired frequency of 922.5 MHz with the ratio of  $(a/s) = 12.25$  for a fixed cell area. A numerical investigation shows that function  $F(a/s)$  can be approximated in the following manner:

$$F(a/s) \approx \frac{\pi}{1.8785} \left\{ \left(\frac{a}{s}\right) + \frac{1}{(a/s)} \right\} - \frac{\sqrt{\log^2\left(\frac{a}{s}\right) + (\pi/3)^2}}{2} \quad (4)$$

This application is adopted to give the best results for ratio of  $(a/s) = 12.25$ , where  $F(a/s) = 19.94276$  that close to  $\pi/1.8785$ . Besides, Equation (2), we can define the resonant frequency of CLWM structure, as given by

$$f_{clwm} = c \left[ \sqrt{2\pi a s \left( \ln \frac{\sqrt{as}}{\pi d} + F(a/s) \right)} \right]^{-1} \quad (5)$$

The ratio of  $(a/s)$  that effects to the resonant frequency ( $f_{clwm}$ ) of CLWM structure is calculated from (5) and plotted, as shown in Figure 6. It is shown that the most proper ratio  $(a/s)$  at 12.25 provides the desired resonant frequency of 922.5 MHz.

Besides, when we take into account the effect of the ratio  $(a/s)$  into (2), the calculated wavenumber  $k_{clwm}$  is around 19.03 rad/m. However, in Figure 7, we observed that the wavenumber  $k_{clwm}$  of waves travelling through the CLWM structure could also be changed when the ratio  $(a/s)$  changed.

Since the structure of CLWM is assemblies of multiple conducting loops

fashioned from aluminum wires with  $a$  and  $s$  are around  $0.3 \lambda$  and  $0.025 \lambda$ , respectively. We can analyze the property of the dense grids of this structure in terms of the effective permittivity in the quasistatic limit by reforming the dispersion equation such the method, the magnetic property of media will be not taken into account, whereas the equation of a frequency-dependent permittivity ( $\epsilon_{eff}$ ) can be expressed in (6).

$$\epsilon_{eff} = \epsilon_0 \left( 1 - \frac{k_{clwm}^2}{k^2} \right) \quad (6)$$

This result from (6) can show that  $\epsilon_{eff} < 0$  for  $k < k_{clwm}$  and  $0 < \epsilon_{eff} < 1$  for  $k > k_{clwm}$ , where  $k$  is the free-space wave number. After we substitute the values of parameters into (6), we obtained the calculated effective permittivity of this structure is around  $2.642 \times 10^{-13}$  F/m.

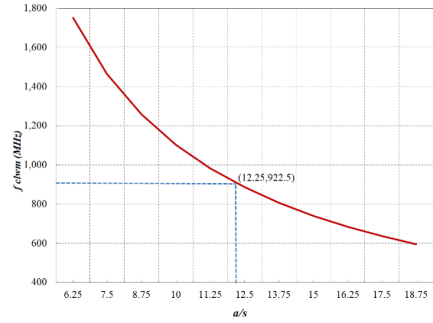


Figure 6. Plot of function of ratio  $(a/s)$  versus  $f_{clwm}$

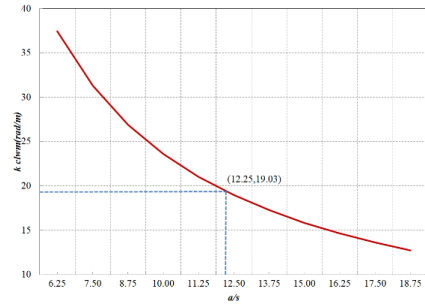


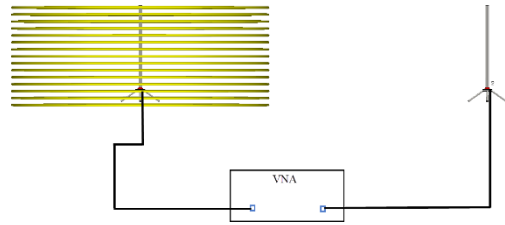
Figure 7. Plot of function of ratio  $(a/s)$  versus  $k_{clwm}$

It is seen that the value of effective permittivity near to zero or so-called that ENZ (Epsilon Near Zero), which is a property of artificial material or metamaterial (Antônio *et al.*, 2013), (Wu *et al.*, 2005) in the class of Near Zero Refraction Index (NZI) (Spada, 2017).

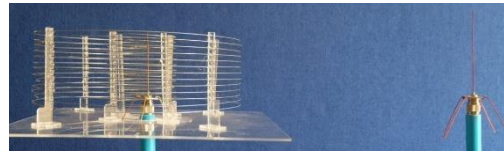
## Experimental Results

In order to characterize the reflection and transmission coefficients of CLWM structure, a measurement setup is prepared, as shown in Figure 8. The measuring system is located in a hostile environment that appropriated for allows non-destructive measurement. The receiving and transmitting antennas are located with the distance in the far-field region for measuring  $S_{11}$  and  $S_{21}$  of CLWM. The proposed antenna is connected to port one as the transmitting antenna. In contrast, the second single monopole that is designed at the same resonant frequency as the receiving antenna is connected to port two of a vector network analyzer. The comparison measured results of  $S_{11}$  of CLWM structure, as shown in Figure 9. We found that the resonant frequency of the measured result is at 922.50 MHz as same as the simulated result and still be good agreement when compared to the simulated result. In Figure 11, the measured  $S_{21}$  of the transmitting antenna (a monopole with/without CLWM) and the same receiving antenna is illustrated to consider the difference of transmission coefficients (around 3.43 dB) between a single monopole to the receiving antenna comparing to the proposed antenna. However, we also measured the gain of a monopole separating from CLWM structure and found that it provides the gain of around 1.3 dB. When this measured gain plus with 3.43 dB, we can obtain the gain of a monopole with CLWM around 4.73 dB.

In Figure 10, it is seen that the magnitude of measured  $S_{21}$  at the same resonant frequency of 922.50 MHz for a monopole antenna with and without CLWM are around -28.65 dB and -32.09 dB, respectively. Therefore, the gain of a monopole antenna with CLWM can be approximated by considering at the different

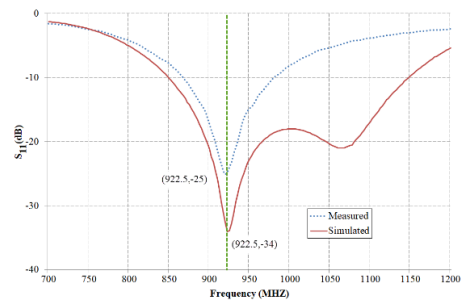


(a) The configuration of the experimental setup.

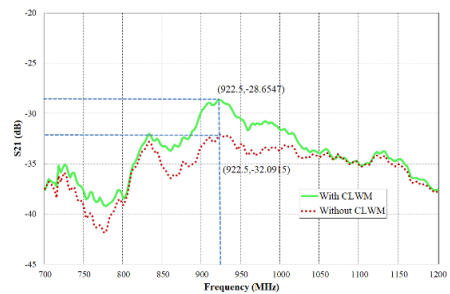


(b) The photograph of the fabricated antenna in measurement setup.

**Figure 8. Measurement setup for  $S_{11}$  and  $S_{21}$  of a monopole antenna with CLWM structure**



**Figure 9. The Comparison of simulated and measured  $S_{11}$  for a monopole antenna with CLWM**



**Figure 10. The measured  $S_{21}$  for a monopole antenna with and without CLWM**

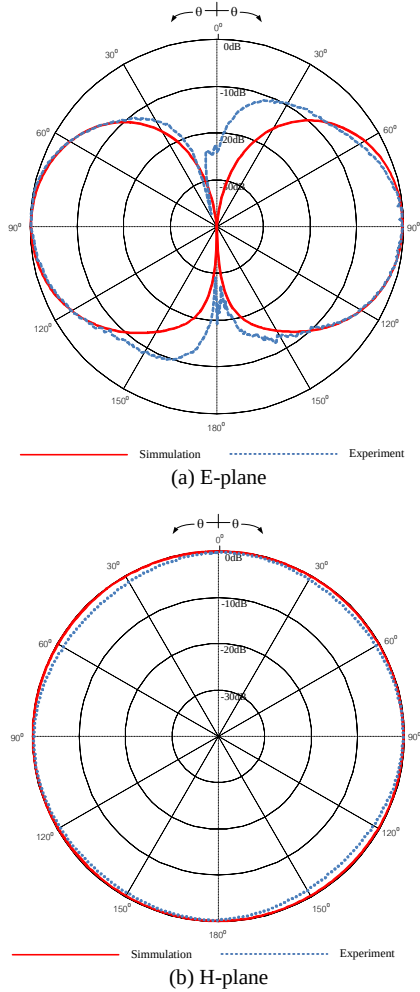
magnitude of  $S_{21}$ . Therefore, its gain is around 3.44 dB over the gain of a single monopole, approximately.

In Figure 11, we show the good agreement between measured radiation patterns in both E- and H- planes of a monopole antenna with and without CLWM structure. It has to be remarked that the radiation patterns of a monopole with CLWM is very close to those of a monopole without CLWM. It is shown that our antenna provides the exact omnidirectional pattern as we required. The 3-dB beamwidths of a monopole

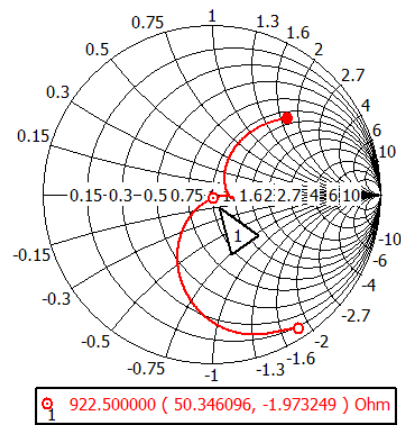
antenna with and without CLWM in E-plane are  $62.9^\circ$  and  $84.3^\circ$ , respectively.

Three geometric parameters of CLWM structure play a critical role for its matching: the inner radius  $r_1$ , the distance of the annular spacing ( $a$ ) and the spacing between the adjacent loops ( $s$ ). When these parameters are optimized as abovementioned, the ability to match the input impedance of the proposed antenna very easily, as displayed in Figure 12. It displays the input impedance of a monopole antenna with CLWM at the resonant frequency of 922.50 MHz is around  $50.346-j1.973\Omega$ .

To confirm that our CLWM structure characterizes the electromagnetic properties of metamaterial and provides the epsilon near to zero. We used the Nicholson-Ross-Wier (NRW) conversion process (Capolino, 2009; Rothwell *et al.*, 2016) to calculate the relative permittivity ( $\epsilon_r$ ) of the CLWM structure. The NRW method used the measurements or the numerical results of the reflection coefficient ( $S_{11}$ ) and transmission coefficient ( $S_{21}$ ) of such the structure located at the middle position between Tx and Rx antennas, as defined as the ratio of reflected or transmitted transverse electric field to incident transverse electric field at the planes of CLWM structure. In general case, the S-parameters can be written as



**Figure 11. Radiation patterns of experimental and simulation of monopole antenna with CLWM @ 922.5 MHz**



**Figure 12. The input impedance of a monopole antenna with CLWM @ 922.5 MHz**

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2T^2}, \quad S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2T^2}. \quad (7)$$

These parameters can be obtained from the network analyzer or numerical results.

The quantities  $\Gamma$  can be determined from the relation of  $S_{11}$  and  $S_{21}$  in term of  $X$ , given by

$$X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}. \quad (8)$$

The solution of the reflection coefficient is

$$\Gamma = X \pm \sqrt{X^2 - 1}, \quad (9)$$

Where  $|\Gamma| < 1$  is required for finding the correct root and in terms of  $S$ -parameter.

Once  $\Gamma$  is determined, the transmission coefficient ( $T$ ) is found as

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}. \quad (10)$$

As abovementioned, since the structure of CLWM is rather dense and considered in the quasistatic limit, which the magnetic property in the material is neglected. Therefore, only the relative permittivity ( $\epsilon_r$ ) of the media will be determined by using the expression

$$\epsilon_r = \mu_r \frac{(1-\Gamma)^2}{(1+\Gamma)^2} \left( 1 - \frac{\lambda_c^2}{\lambda_0^2} \right) + \frac{\lambda_c^2}{\lambda_0^2} \frac{1}{\mu_r}, \quad (11)$$

where  $\lambda_0$  is free space wavelength,  $\lambda_c$  is the cutoff wavelength. However, this is only valid for permittivity measurement as this equation assumes  $\mu_r = 1$ .

By measuring the amplitude and phase of reflection and transmission coefficient in the laboratory, we obtained  $S_{11} = 0.12288 \angle -86.909^\circ$  and  $S_{21} = 0.21246 \angle 121.581^\circ$ . Substituting these values into (7)-(8) and then

bring results substituting into (9)-(11), we obtained the relative permittivity ( $\epsilon_r$ ) is around 0.647. Finally, we converted  $\epsilon_r$  to the frequency-dependent permittivity ( $\epsilon_{eff}$ ) is around  $5.721 \times 10^{-12} \text{ F/m}$ . It is noted that the quantity of epsilon still be near zero and in the class of NZI.

## Conclusions

This paper discusses the method for increasing the gain of a quarter-wavelength monopole antenna with the aim that its omnidirectional pattern must be retained. The metamaterial technique based on the CLMW structure, -fabricated from the aluminum wires-, has been designed and surrounded such the monopole to provide the higher gain and the desired patterns. When the dimension of this prototype structure is optimized, the CLWM structure can efficiently cooperate with a monopole antenna at the desired frequency of 922.50 MHz with excellent matching ( $S_{11} = -24.98 \text{ dB}$ ), higher gain ( $\sim 4.73 \text{ dB}$ ), wider bandwidth ( $\sim 301.2 \text{ MHz}$  @  $S_{11} = -10 \text{ dB}$ ), improved radiation efficiency ( $e_{cd} = 0.0354 \text{ dB}$ ) and exact omnidirectional pattern.

We also discussed the proposed structure wire media that it is so-called CLMW. The classical theory of dispersion and reflection from media has been applied and modified for our structure to find the frequency-dependent permittivity of CLWM structure ( $\sim 2.642 \times 10^{-13} \text{ F/m}$ ). Nevertheless, we also investigated the effective permittivity of the structure using the procedure of Nicholson-Ross-Wier to confirm that our structure has the epsilon near zero ( $\sim 5.721 \times 10^{-12} \text{ F/m}$ ). Finally, it has been shown that the CLWM structure has electromagnetic property of metamaterials.

As a result, we concluded the proposed CLWM structure is appropriate for increasing the gain of the monopole antennas, especially when we still need the radiation pattern of the modified antenna to be omnidirectional. This structure can easily be applied to any monopole antenna by only design the turn number of circular loop according to the whip length of the given monopole.

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