Design of Circle Defected Waveguide with Monopole Antenna

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Abstract. In this paper, the circle DWS with monopole antenna is designed and studied. From previous research studies, there are design of waveguide with metamaterial by using Electromagnetic Bandgap (EBG) and Frequency Selective Surface (FSS). Yet, Defected Waveguide Structure (DWS) is not familiar to design with waveguide which is the motivation of this paper. Meanwhile, the design of waveguide with monopole antenna is not explored widely. The DWS is designed in circle shape with Ultrawideband (UWB) monopole antenna. Several factors are studied on the size, inter element spacing and number of circle DWS towards waveguide. Circle DWS with monopole antenna are analyzed through antenna parameters such as return loss, efficiency, gain and directivity. In overall, the circle DWS with monopole antenna able to operate in wide bandwidth of 8.66GHz which is suitable for UWB applications. It also achieves higher efficiency which is more than -3dB. Highest gain of 7.29dB and directivity of 8.62dBi are achieved at 9GHz and 9.5GHz respectively. The use of DWS improves the gain and directivity of low profile monopole antenna but at the same time still maintaining the its wide bandwidth.

1. Introduction
A great deal of attention is dedicated to metamaterial in recent year. This is because it consists of material properties that is made artificially by man [1]. There are a few examples of metamaterial such as Electromagnetic Bandgap (EBG), Frequency Selective Surface (FSS), Defected Ground Structure (DGS) and Defected Microstrip Structure (DMS) [2-5]. Defected structure which are designed at ground plane and microstrip feed line will be called as DGS and DMS. In the past, defected structure is designed in patch or slot to disturb the normal current distribution. For example, DGS in [4] enhances bandwidth while DMS in [5] introduces higher gain. Despite there are defected structure on the ground plane and microstrip feed line, no researches on the Defected Waveguide Structure (DWS) is obtained.

For the past, waveguide is one the earliest types of transmission line used to transmit signal [6]. Nowadays, it has been focused on the applications especially in antenna and filter site [7-8]. Besides that, it also has been designed with metamaterial to determine its reflection and transmission characteristics [9]. There is theoretical modal used to study the field distribution of waveguide with anisotropic walls [10]. The anisotropic walls are referred to walls with metamaterial. From the previous studies, there are types of metamaterial such as FSS, EBG [9, 11] are designed with waveguide but no DWS design is found with waveguide.

There is another hot research topic which is Ultrawideband (UWB) technology [12-13]. This is because people request for the wide coverage for high date rate and high resolution. Thus, UWB
technology requires wideband antenna for operation. Monopole antenna is of great interest for its potential of low profile and low cost [13-15]. There are researches are done for the modifications on monopole antenna by using metamaterial by internally or externally [15-16]. For instance, the DGS improves the bandwidth of monopole antenna by introducing L-shaped DGS slot at ground plane in terms of internally [15]. For external, FSS reflector is placed underneath monopole antenna achieves enhancement in gain [16]. However, there is no DWS design with monopole antenna is found.

In this paper, the circle DWS waveguide is designed with monopole antenna. The monopole antenna is a microstrip-fed with circular radiating patch which is worked for UWB frequency range 3.1GHz-10.6GHz. The circle DWS waveguide is designed externally to the monopole antenna. Antenna parameters such as return loss, efficiency, gain and directivity are used to observe its performance.

2. Antenna Design

The design and simulation are constructed in CST Microwave Studio. Monopole antenna is designed in circular radiating patch and microstrip feed line. This antenna is designed to support UWB applications at 3.1GHz-10.6GHz. The Equations (1) and Equations (2-4) are referred for the fundamental of circular radiating patch and microstrip feed line. There are two copper layers at front and back of substrate where circular radiating patch and feed line at the front while a ground plane at the back as shown in Figure 1. The material used for antenna design is FR4 substrate with dielectric constant 4.4, tangent loss 0.019 and thickness 1.6mm.

Radius of circular radiating patch can be determined by using equations as below [17]:

\[
R = \frac{F}{\sqrt{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]}}
\]

where
\[\begin{align*}
R &= \text{actual radius} \\
F &= 8.791 \times 10^9 \\
f_r &= \text{resonant frequency} \\
h &= \text{substrate height} \\
\varepsilon_r &= \text{substrate dielectric constant}
\end{align*}\]

The feed line can be also calculated by using the microstrip feed line equations as below [6]:

Characteristic impedance, \(Z_o\)

\[
Z_o = \begin{cases} 
\frac{60}{\sqrt{\varepsilon_{reff}}} \ln \left( \frac{8h}{W_f} + \frac{W_f}{4h} \right) & \text{for } \frac{W_f}{h} < 1 \\
\frac{120\pi}{\sqrt{\varepsilon_{reff}}} \left[ \frac{W_f}{h} + 1.393 + 0.667 \ln \left( \frac{W_f}{h} + 1.444 \right) \right] & \text{for } \frac{W_f}{h} > 1
\end{cases}
\]

where \(W_f = \text{line width}\)

Effective dielectric constant, \(\varepsilon_{reff}\)

\[
\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \sqrt{\frac{1}{1 + \frac{h}{W_f}}}
\]
Typically, dimension of waveguide (width x height) is important to determine cut off frequency as shown in Equation (5). Equation (5) shows the relationship between width \((a)\) and height \((b)\) with cut off frequency \(f_c\) [6]. The larger the \(a\) and \(b\), the smaller the \(f_c\) can be propagated through waveguide where \(m\) and \(n\) represent the modes of waveguide. However, the rectangle waveguide with full copper at inner walls is designed based on the dimension of monopole antenna as shown in Figure 2. The waveguide width \((a=44\, \text{mm})\) and height \((b=52\, \text{mm})\) which include dimension and small vacuum gap of 1mm to avoid both waveguide and antenna surface are contacted. Two waveguide ports are set at both open-ended surfaces of waveguide to measure the transmission coefficient (S21).

\[
f_c = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}
\]

(5)

In this paper, the DWS waveguide in circle shape is focused instead of waveguide with full copper. The copper layer at the inner walls of waveguide are removed to have circle DWS. The simple basic circle shape is utilized due to ease of fabrication. Throughout the designs, radius refers to the radius of circle while space refers to the inter element spacing. Meanwhile, variable \(X\), \(Y\) and \(Z\) refer to number of circle element according \(X\), \(Y\) and \(Z\) directions respectively at top bottom and both sides walls. Initially, the circle DWS are designed with \(\text{Radius}=3\, \text{mm}, \text{Space}=1\, \text{mm}, \text{X}=2, \text{Y}=3\) and \(\text{Z}=15\) as shown in Figure 3.
Before the circle DWS waveguide is inserted with monopole antenna, a few parameter studies are done to determine effects of DWS towards waveguide. The parameter studies are done on the Radius, Space and number of circle element for X, Y and Z directions. The circle DWS waveguide is designed with full circle DWS to insert monopole antenna as shown in Figure 4. In addition, the number of circle DWS in Z direction is 12 to ensure a full wave cycle for propagation of longest wavelength in waveguide. Their performances are observed and analyzed through S-Parameters which are reflection coefficient ($S_{11}$) and transmission coefficient ($S_{21}$). As seen in Figure, the monopole antenna is then acted as input to the circle DWS waveguide. Antenna parameters in terms of return loss, efficiency, gain and directivity is observed for the circle DWS with monopole antenna.

3. Result and discussion
The parameter studies of the circle element are done on its size and internal circle element spacing as shown in Figure 5-6. The size of circle element is varied in terms of radius from 3.0mm-6.6mm. It is observed that the S-Parameters results are heavily depended on the size of circle element. Smaller size of circle element with radius=3.0mm can achieve widest bandwidth at 3GHz-9GHz for transmission as shown in Figure 5. For convenience in description, the S-Parameters results is enlarged and divided into two groups in terms of transmission and reflection. The bigger the size of circle element, the narrower the operating band and the higher the reflection at higher frequency.
Less significant changes are observed through the S21 results by varying the inter element spacing in Figure 6 compares to size. They vary tardily but significant changes only occur at higher frequency range at 9GHz onwards. The optimized inter element spacing for circle DWS is 3mm with widest bandwidth of 6.5GHz. In Figure 6, almost similar curve is achieved for S11 below 5.5GHz. Above 5.5GHz, the S11 with bigger space fluctuate more rapidly to have more cycles with higher phase changes compare to S11 with smaller space.

Meanwhile, the number of circle DWS is also varied in X, Y and Z directions. The number of circle DWS in Z direction still maintain in $Z=15$. While varying the number of circle DWS in X direction, the number of circle DWS in Y direction is designed to occupy fully at the walls with maximum number of Y and vice versa. It is noticed that the variance of number in X direction has no impact on the reflection and transmission of waveguide as shown in Figure 7. However, Figure 8 shows there is an obvious change for S21 at 8GHz and onwards for the variance of number in Y direction. With no circle DWS at both sides walls, the waveguide can achieve high pass at 4GHz with higher transmission and low reflection. Besides that, fluctuated S11 with biggest different in 25dB is achieved for $Y=0$. While adding the number of circle DWS, the S11 is changed faster in terms of phase to have narrower cycle of S11. However, there is improvement on transmission at lower frequency range when adding the number of circle DWS in direction Y.
Figure 7. S-Parameters results by varying number of circle DWS in X direction

Figure 8. S-Parameters results by varying number of circle DWS in Y direction

For the length of circle DWS waveguide, the number of circle DWS in Z direction is varied from number 5-30. As seen in Figure 9, the more the number of circle DWS in Z direction, the lower the transmission at higher frequencies. It is understood that with the increasing of number in Z direction, the longer the circle DWS waveguide, more losses are occurred in transmission especially at high frequencies. In zoomed view of Figure 9, the shorter waveguide with Z=5 shows biggest difference of fluctuated S11 with 25dB. By adding the number of Z, the S11 results tend to have one more cycle but smaller change in magnitude dB. For S21, shorter waveguide with least number in Z direction shows higher transmission and wider working band at higher frequency. In Figure 9, the S11 in phase is showed at frequency 5GHz-10GHz. It is observed that almost similar position but different in degree of phase are achieved for all designs at frequencies 6.02GHz and 8.08GHz. The shortest waveguide demonstrates lowest in phase at both frequencies.
Figure 9. S-Parameters results by varying number of circle DWS in Z direction

Figure 10. S11 in phase view at frequency 5GHz-10GHz

Design of circle DWS with monopole antenna is observed through return loss, efficiency, gain and directivity as shown in Figure 11. For return loss, it achieves wide bandwidth of 8.66GHz at 2.34GHz-11GHz with two resonances at 3.386GHz and 8.624GHz. Besides that, the efficiency is more than -3dB to ensure more than 50% of the signal can be radiated successfully. Furthermore, it can achieve more than 2dB and 2dBi for gain and directivity respectively. Both directivity and gain show almost similar curve with highest directivity and gain are 8.62dBi at 9.5GHz and 7.29dB at 9dB. Almost high directivity and gain are achieved at lowest resonant frequency 8.624GHz.
Figure 11. Antenna parameters results circle DWS with monopole antenna

The surface current distribution is also observed at a few interested frequencies. They are plotted at phase=90 degree in Figure 12. It is noticed that bottom wall has less concentration of surface current compares to side wall. From the side wall, the transmission of wave can be observed. At 2GHz, the distribution of surface current is only occurred near monopole antenna due to longest wavelength in propagation. At first resonant frequency 3.386GHz, higher concentration of surface current is achieved at side wall. This show the propagation of wave is occurred through circle DWS waveguide. Surface current is also distributed at the side wall but with less concentration due to high reflection at 4.637GHz. Meanwhile, at second resonant frequency 8.624GHz, the surface current distribution is occurred at both side and bottom walls. Higher concentration of surface current still can be promised due to lowest reflection and high gain at higher frequency.

Figure 12. Surface current distribution of circle DWS with monopole antenna at different frequencies

4. Conclusion
This paper presents and studies the circle DWS with monopole antenna. Basically, a few factors for circle DWS towards waveguide are studied which includes size, inter element spacing and number of circle DWS. The design of circle DWS with monopole antenna still able to work in wide bandwidth of
8.66GHz at 2.34GHz-11GHz. In addition, the efficiency is higher than -3dB to ensure the satisfactory radiation. Furthermore, it can achieve higher gain and directivity with more than 2dB and 2dBi respectively. Highest gain and directivity are occurred at higher frequency range. In future, this circle DWS with monopole antenna will be fabricated for verification purpose. Besides that, others shape will be also used to replace the circle DWS to study the effects towards waveguide.

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5. References

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