A New Loop Antenna for Directional UWB Links

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Abstract

Loop antennas of circumference greater than a wavelength are generally known to have a good directive radiation pattern. However, for use in UWB applications, the variation of the radiation pattern with frequency must also be taken into account. Besides a good wideband radiation pattern, the impedance bandwidth of the antenna is also very important. The quality of a transmitted and received UWB pulse from the antenna will be a combination of both these factors. In this paper, we first investigate the characteristics of loop antennas with respect to both these factors. Next, we propose a new loop antenna configuration to overcome the limitations of the standard loop antenna for UWB applications. The new antenna consists of two concentric half-loops directly coupled to each other. The proposed antenna is analyzed using the Method-of-Moments (MoM). The theoretical and measured results agree with each other closely and attest to the fact that the new antenna has a far superior impedance bandwidth when compared with conventional loop antennas. Further, it is shown that the new antenna has a good gain and a useful radiation pattern for directional wireless links. The advantages of the antenna are conclusively demonstrated by successfully deploying it in a very high speed (500 Mbps) point-to-point UWB link.

1. Introduction

The circular wire loop is a very commonly encountered structure in the study of antennas. The most commonly encountered forms of loop antennas are typically a fraction of a wavelength in circumference. These electrically small loop antennas can be treated as magnetic dipoles and provide a similar radiation pattern to those of electric dipoles. However, the radiation characteristics of the loop antenna starts to change drastically as its circumference exceeds half a wavelength. At a circumference of one wavelength, the loop antenna exhibits maximum radiation along its axis and is considered to be as fundamental as the half-wavelength dipole in the field of radiating structures. While these one wavelength circumference loops have been extensively studied and used in Yagi-Uda arrays [1], the potential of larger than one wavelength circumference loops as radiating structures have been given scant notice. This is probably due to the physically large size of these antennas in the less than 1 GHz bands that were commonly used in the past.

At present, the most commonly used FCC allocated band for UWB is in the 3.1 GHz to 10.6 GHz range. At these frequencies, loop antennas of a few wavelengths in circumference can still be considered to be physically small for many UWB applications. Thus in this paper we first investigate the radiation and impedance characteristics of electrically large (but physically small) loop antennas. We then propose suitable modifications to the standard loop antenna to make it more ideal for UWB applications. The improvement in performance of the proposed antenna are highlighted through simulations and measurements. Finally, the new antenna is utilized in a UWB system where its particular characteristics can be used most advantageously.

2. Characteristics of Conventional Half-loop Antennas

The standard circular loop antenna is a balanced structure and so requires the use of a balun when fed by a coaxial line, which is an unbalanced transmission line. One way to avoid the use of a balun is to use a half-loop configuration fed by a coaxial probe through a ground plane. This configuration also allows the measurement of the loop characteristics without the need to de-embed the effects of the balun. Thus, for practical purposes, the probe-fed half-loop antenna has been used in this work instead of the full loop.

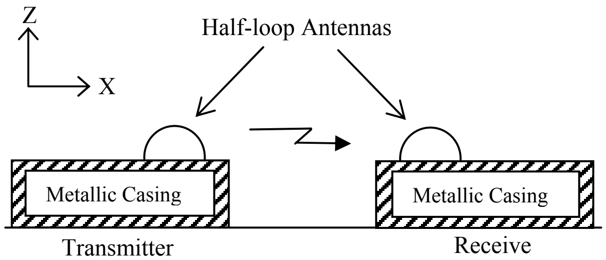


Figure 1. Half-Loop Antennas in a Point-to-Point UWB Link

Often it is assumed that antennas with highly directional patterns are not suitable for UWB applications. However, it is not true that all UWB applications require omni-directional antennas. In fact, for the case of point-to-point UWB links, directional antennas give rise to a better link performance than omni-directional antennas. One possible configuration for the use of ground plane or casing mounted half-loop antennas in directional UWB systems would be that shown in Figure 1. In this configuration, the radiation pattern in the (X-Y) azimuthal plane would be most crucial. The radiation pattern of loop antennas can be easily obtained by first obtaining the Fourier series coefficients of the currents on the antenna. Storer [2] and Wu [3] have provided a formulation for evaluating the Fourier coefficients of the loop current. More recently, Sivanand et al. [4] have reported a general formulation for calculating the Fourier coefficients for the currents on an array of arbitrarily oriented loop antennas. Using the Fourier coefficients, the radiation pattern can be obtained in a straight forward manner using the closed form expression by Li et al. [5]. Figure 2 shows the azimuthal far-field radiation pattern at 1, 3 and 5 GHz for a half-loop with a radius of 4.8 cm. The dimensions of the antenna corresponds to a semi-circular circumference of half-a-wavelength at 1 GHz. As expected, the directional properties of the half-loop antenna are seen to improve at higher frequencies when its circumference is in the order of a few wavelengths.

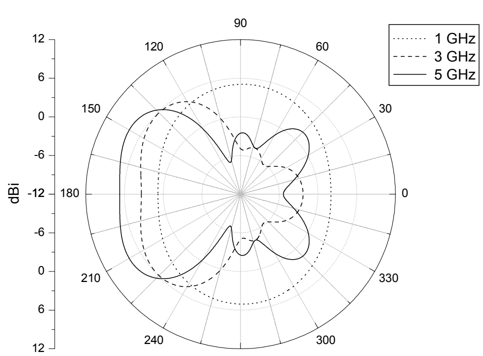


Figure 2. Azimuthal Radiation Pattern (X-Y) Plane of Half-Loop Antenna

In order for the antenna to be useful as a wideband radiator, its impedance bandwidth has to be acceptable as well. For this, the Fourier coefficients of the current on the loop are evaluated for a range of frequencies. The input admittance is then given by the following simple relation:

$$Y_{in} \approx \sum_{n=-n\max}^{n\max} 2I_n \tag{1}$$

where I_n are the Fourier coefficients of the loop current. A value of nmax equal to 20 has been verified to give a result which is very close to actual measurements [6]. From the input admittance, the return loss of a half-loop antenna with radius of 4.8 cm is plotted in Figure 3. It is seen that impedance bandwidth of the loop antenna is quite bad. A satisfactory input impedance with S11 less than -10 dB is only achieved over a small frequency band between 1.05 GHz and 1.15 GHz.

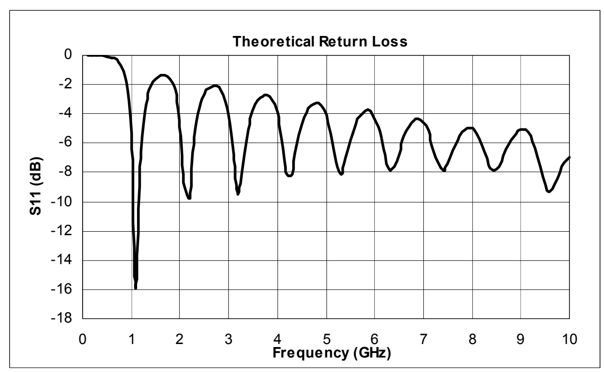


Figure 3. Theoretical Return Loss of Half-Loop Antenna

So, although the half-loop antenna has a good directive pattern, it suffers from a narrow impedance bandwidth. In the next section, a modified half-loop structure is proposed for overcoming the impedance bandwidth limitations of the conventional half-loop antenna while retaining its good radiation pattern characteristics.

3. The New Direct-coupled Concentric Half-loop Antenna

Figure 3 shows that the half-loop has a resonant behavior that repeats approximately at frequency intervals at which the circumference increases by about half a wavelength. So it was suspected that a new parallel structure consisting of two loops with different radii would have a more broadband combined impedance characteristic. Thus the proposed new antenna is a parallel loop structure (Figure 4) consisting of two direct-coupled concentric half-loops. As in the case of the earlier discussed conventional half-loop, the proposed antenna is also mounted on a ground plane and the inner loop is directly fed by the same source as the outer loop.

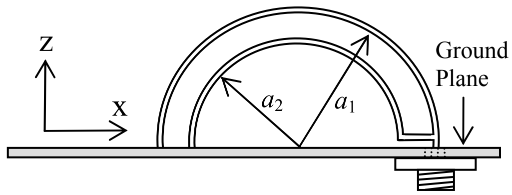


Figure 4. Geometry of the Proposed Direct-Coupled Concentric Half-Loop Antenna

3.1 Method of Analysis for Proposed Antenna

In this section, a Method-of-Moments analysis of the new antenna is presented. The analysis will allow the Fourier current coefficients on the two loops of the antenna to be determined. From the Fourier current coefficients, the input impedance and radiation pattern can be easily determined.

The outer loop is referred to as *Loop 1* and inner loop as *Loop 2*. By making use of the boundary condition for the electric field on the antenna surface and after several steps of simplification, the following concise expression relating the antenna excitation voltage, V, to the loop current, I, for the two concentric half-loops is arrived at:

$$V_p\delta(\phi_p)=\frac{j\eta}{4\pi k}\sum_{q=1}^{2}[\int_{-\pi}^{\pi} I_q(\phi'_q)\{\frac{\partial^2 G^{pq}}{\partial\phi_p^2}+k^2G^{pq}(\phi_p-\phi'_q) .\cos(\phi_p-\phi'_q)a_pa_q\}d\phi'_q] \qquad p=1,2 \tag{2}$$

where

$$G^{pq}(\phi_p-\phi'_q)=\frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{e^{-jkr^{pq}[(\phi_p-\phi'_q),\zeta_q]}}{r^{pq}[(\phi_p-\phi'_q),\zeta_q]} \tag{3}$$

$$r^{pq}[(\phi_p-\phi'_q),\zeta_q]=[(a_p^2+a_q^2)-2a_pa_q\cos(\phi_p-\phi'_q)+4b_q^2\sin^2(\zeta_q/2)]^{0.5} \tag{4}$$

and k is the propagation constant, a is the loop radius, b is the wire radius and ζ describes the angular variation around the wire cross-section. To solve (2), the function G^{pq} and loop current I_q are expanded into a Fourier series:

$$G^{pq}(\phi_p-\phi'_q)=\sum_{n=-\infty}^{\infty}g_n^{pq}e^{-jn(\phi_p-\phi'_q)} \tag{5}$$

$$I^q(\phi'_q)=\sum_{n=-\infty}^{\infty}I_n^q e^{-jn\phi'_q} \tag{6}$$

Using (5) and (6) in (2) and simplifying, the following set of linear equations is obtained:

$$V_p=j\eta\pi[\alpha_m^{p1}I_m^1+\alpha_m^{p2}I_m^2] \quad p=1,2 \tag{7}$$

where

$$\alpha_m^{pq}=\frac{ka_pa_q}{2}(g_{m+1}^{pq}+g_{m-1}^{pq})-\frac{m^2}{k}g_m^{pq} \tag{8}$$

and

$$g_m^{pq}=\frac{1}{2\pi}\int_{-\pi}^{\pi}G^{pq}(\phi_p-\phi'_q)e^{jm(\phi_p-\phi'_q)}d(\phi_p-\phi'_q) \tag{9}$$

As the inner loop is fed by the same source as the outer loop, the phase difference in the excitation of the loops is taken into account by treating the feed to the inner loop as a two-wire line. Thus, we set the excitation voltages in (7) to be: $V_1=1$ and $V_2=e^{-jk(a_1-a_2)}$. Once the Fourier series coefficients of the currents in each loop are obtained, their individual input admittance is found from (1). Next, the total input admittance, Y_{in}, at the probe feed is obtained by impedance transformation of the input admittance, $Y_{in}^{(2)}$, of the inner loop to the feed point and summing it with the input admittance, $Y_{in}^{(1)}$, of the outer loop:

$$Y_{in}=Y_{in}^{(1)}+Y_0\frac{Y_{in}^{(2)}+jY_0\tan k(a_1-a_2)}{Y_0+jY_{in}^{(2)}\tan k(a_1-a_2)} \tag{10}$$

If the feed wire has a radius of b and is raised above the ground by a height h, the characteristic admittance of the feed line in (10) is given by :

$$Y_0=1/(120\cosh^{-1}(h/b)) \tag{11}$$

3.2 Impedance and Radiation Characteristics

The impedance bandwidth characteristics of the proposed antenna consisting of an outer half-loop of radius 4.8 cm and inner half-loop of radius 4.0 cm was investigated. The theoretical return loss, using MoM, of the proposed antenna is shown in Figure 5. The theoretical results clearly show that the proposed antenna has a much wider impedance bandwidth than the single half-loop. Its -10 dB impedance bandwidth extends all the way from 4 GHz to 10 GHz.

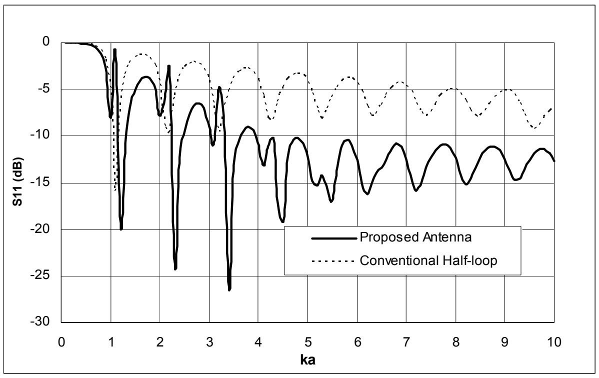


Figure 5: Theoretical Return Loss of Proposed Antenna

To verify the theoretical results for the conventional half-loop (Figure 3) and the proposed concentric loop antenna (Figure 5), both of them were fabricated and measured. The measured results are shown in Figure 5. For the conventional loop case, the measured S11 indicates a narrow bandwidth as predicted by the analysis. The -10 dB bandwidth has shifted down slightly to 0.95 GHz to 1.05 GHz. For the case of the proposed antenna, the measured result indicates an impedance bandwidth of more than 50%, from 4.5 GHz to 7.9 GHz. Considering fabrication tolerances, the measured results for both cases can be said to agree very well with the theoretical results.

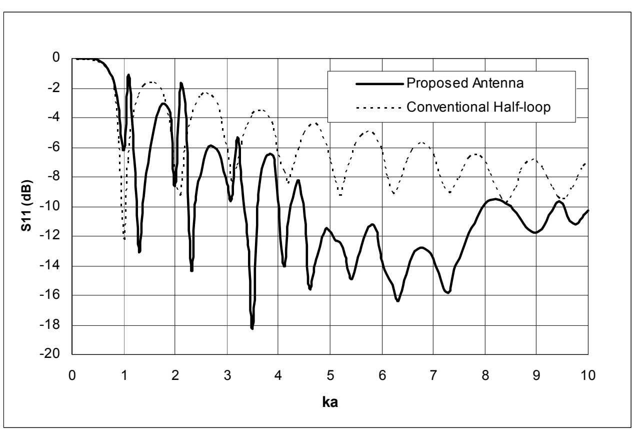


Figure 6: Measured Return Loss of Proposed Antenna and the Conventional Half-Loop Antenna

Using the Fourier current coefficients from the MoM analysis, the far-field radiation from each loop in the new antenna is ascertained in the same manner as that of the half-loop in Section 2. As both loops of the proposed antenna are in the same orientation, the total far-field radiation pattern is obtained easily by summing the corresponding vector field of each loop. The azimuthal (x-y plane) radiation patterns of the proposed antenna at 3 frequencies, 5.5 GHz, 6.5 GHz and 7.5 GHz are shown in Figure 7. It is clear that the proposed antenna provides a highly directive pattern in the 'Azimuthal angle =180°' or '-*x*' direction, with a gain that varies little over the frequency range. This directive pattern is very useful for high speed directional UWB links where the smaller back-lobe helps to reduce the effect of unwanted reflections and in turn lowers the amount of inter-pulse interference.

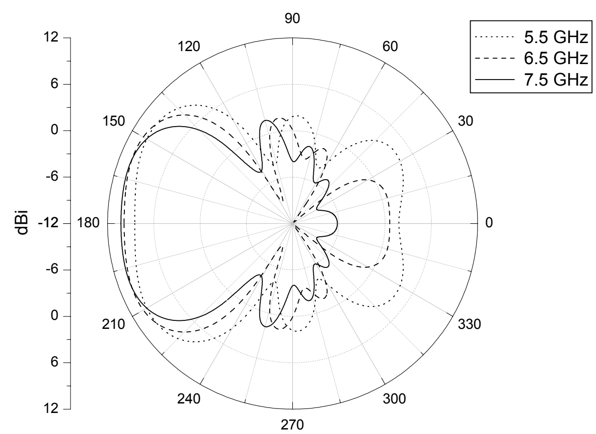
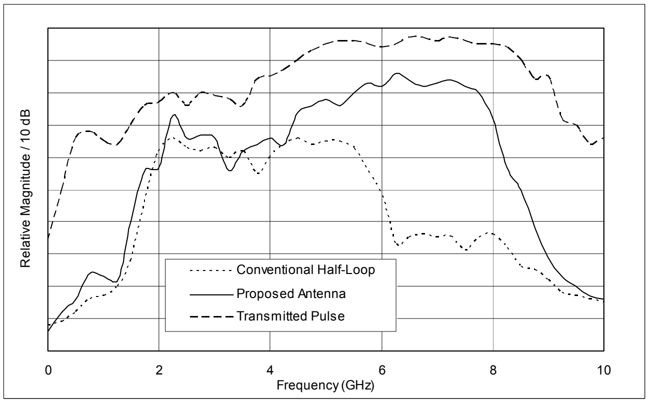
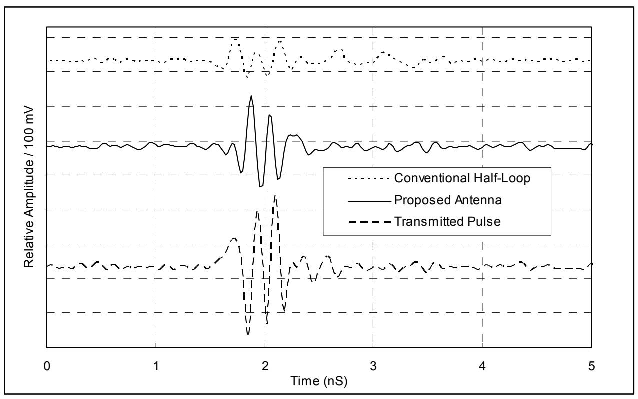


Figure 7: Azimuthal Radiation Pattern (X-Y) Plane of Proposed Antenna

To evaluate the use of the proposed antenna for UWB applications, a 5 to 8 GHz band pass filtered pulse with a center frequency of 6.5 GHz and width of about 0.4 ns was transmitted and received 2 metres away. Similar antennas were used for both transmitting and receiving. The received signals were amplified and measured both in time as well as frequency. The spectral and temporal characteristics of the transmitted pulse and the received pulse for the cases of the conventional single half-loop and the proposed new concentric loop antenna are shown in Figure 8. The spectral characteristics (Figure 8a) clearly shows that the proposed antenna allows more energy from the transmitted signal to be received, especially in the 4.5 GHz to 8.5 GHz region. The time domain measurements shown in Figure 8b supports this fact. The pulse received by the proposed antenna is seen to be of a higher amplitude and better fidelity when compared with that received by the conventional half-loop.



(a)



(b)

Figure 8: Measured Characteristics of Transmitted and Received Pulses. (a) Spectral and (b) Temporal

4. Application of New Antenna in a Directional UWB Link

A high speed UWB link was set up to test the applicability of the new antenna for point-to-point or directional applications. The setup basically consisted of a transmitter and receiver separated by a distance of 2 metres in a reasonably cluttered laboratory environment. To help the reader understand the test setup, a brief description of the transmitter and receiver are given here. More details can be found in [7-9] where the components and performance of a similar setup have been described.

The transmitter is as shown in Figure 9. It consists of an in-house built 500 MHz pulse repetition frequency (PRF) pulse generator, band pass filter (BPF), wideband mixer modulator, pattern generator and transmit amplifier. The transmitted pulse is the same as that used in Section 3 except that it has a much higher PRF. The pulse has been band pass filtered to ensure that most of the energy lies within the 5.5 GHz to 7.5 GHz bandwidth of the antenna. The pattern generator is set to repeatedly generate a differentially coded PN9 sequence. This sequence is used to modulate the generated pulses. The output of the modulator is a BPSK modulated pulse train with a pulse-to-pulse spacing of 2 ns.

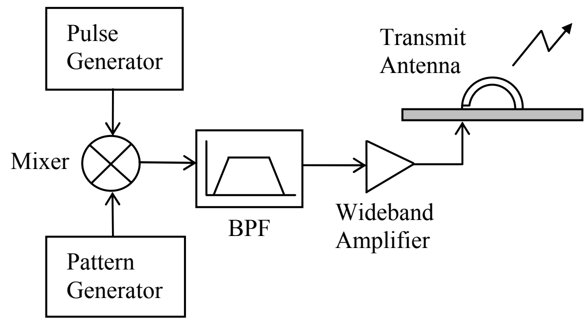


Figure 9: Schematic of Transmitter in Test Setup

The receiver is shown in Figure 10. A 5 to 8 GHz front-end BPF is used to reject unwanted interfering signals as the test is conducted in a laboratory environment and not in an anechoic chamber. The filtered signal is passed to a delayed reference correlator consisting of a 2 ns cable delay and wideband mixer. A 1 GHz low pass filter (LPF) is used after the correlator to act as an integrator and also to reject the high frequency leakage signals from the mixer. A comparator with hysteresis is used to convert the analog signal from the LPF to a binary digital signal. The digital signal is passed to a clock recovery circuit which feeds the clock and re-timed data signals to a Bit-Error-Rate (BER) tester. Using these two signals, the BER tester is able to compare the recovered data with a stored PN9 sequence and provide a value for the BER.

At a distance of 2 metres between the transmit antenna and receive antenna, a BER of less than 10^{-5} was consistently achieved at different locations in the laboratory. As one pulse was used to represent each bit of information, the data rate is the same as the pulse repetition frequency and hence 500 Mbps. No additional error correction coding was used and hence all the data transferred were information bits. Thus the BER performance can be considered to be sufficient for most practical purposes. This result, though not directly linked to the performance of the antenna, is definitely a conclusive indication that the proposed antenna is a strong candidate for use in directional or point-to-point UWB links.

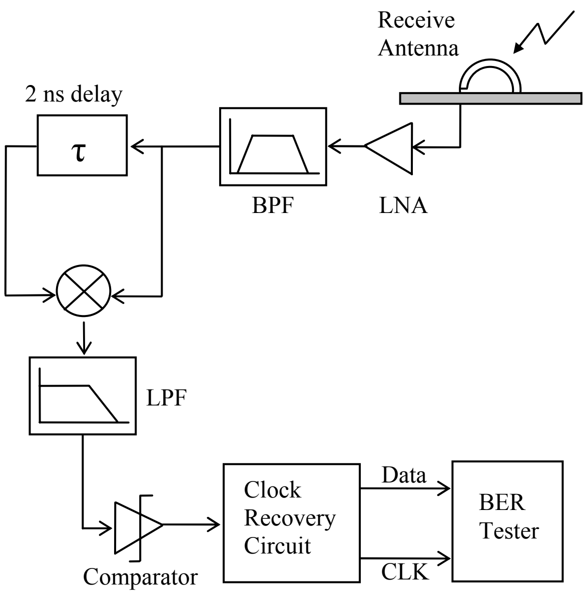


Figure 10: Schematic of Receiver in Test Setup

5. Conclusion

This paper first shows that loop antennas of a few wavelengths in circumference have a highly directive pattern which is suitable for directional UWB links. However, the impedance bandwidth of conventional loop antennas are seen to be insufficient for UWB applications. To overcome this bandwidth limitation and still take advantage of the good radiation pattern of the loop antenna, a new structure consisting of a pair of direct-coupled concentric half-loops is proposed A concise formulation for analyzing the antenna using MoM is provided. Both the theoretical results as well as measurements indicate that the proposed antenna has much better wideband properties than single half-loops. The radiation pattern of the antenna is directional and provides a high gain which is relatively constant over a wide range of frequencies. This allows the antenna to be used in directional UWB links without the use of absorbers for reducing reflections due to back-lobes. For a particular configuration, the antenna bandwidth was measured to be in the range of 4.5 GHz to 7.9 GHz. These characteristics were used advantageously in a very high speed UWB link working at 500 Mbps. The BER of the link was measured to be better than 10^{-5} at a distance of 2 metres between the transmit and receive antenna. This good performance of the link is a clear proof of the potential of the proposed 'Direct-Coupled Concentric Half-Loop' antenna as a low cost option in high speed point-to-point UWB links.

6. References

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