Research and design of tripod-shaped UWB antenna for GPR

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Abstract. In recent years, GPR (Ground Penetrating Radar) has developed rapidly and has played an important role in many fields. As a key part of GPR, the antenna directly affects system performance. A suitable antenna can greatly improve the detection results. To this end, this paper introduces the design of GPR tripod-shaped ultra-wideband antenna based on bow tie antenna. The working bandwidth of the antenna is widened by means of structural loading with truncation as the main part and circular slot at the end of the antenna. Antenna optimization and simulation were performed using ANSYS HFSS (High Frequency Structure Simulator), and the effects of antenna arm truncation length on antenna performance were discussed. Simulation results show that the designed antenna has an operation bandwidth of 700MHz – 2GHz and good directionality. It is a miniaturized ultra-wideband antenna suitable for shallow underground pipeline detection.

1. Introduction
GPR is widely used in many fields, such as pipeline inspection, underground cavity detection, buried mine detection, moon and polar exploration, because of its advantages of high efficiency, fast and nondestructive detection [2,8]. At present, an important research direction of GPR is the research and design of matching antenna [4].

Compared with traditional radar, the working principle of GPR is same, but compared with the air propagation medium of traditional radar, the working environment of GPR is more complex. In order to obtain higher resolution and better detection depth and portability, GPR antenna has its own unique requirements in directivity, working bandwidth, gain and size, among which the working bandwidth of antenna determines the application of GPR system [1]. In addition, the resolution of GPR system is directly proportional to the antenna bandwidth, so it is usually required that the wider the antenna bandwidth is, the better, that is the so-called ultra-wideband antenna.

In the scientific practice of ground penetrating radar for many years, the commonly used antenna types include bow tie antenna, Vivaldi antenna, spiral antenna, horn antenna etc. But the most widely used is bow tie antenna. SenSoft's Noggin1000 product uses a 1GHz main frequency antenna to detect road conditions; GSSI's RoadScan product uses 1GHz and 2GHz antennas to detect road conditions at a depth of about 1m [7]. In current commercial ground penetrating radars, narrowband antennas are often used. When detecting targets at different depths, antennas with different main frequencies must be replaced, and the resolution is limited. So the research of GPR ultra-wideband antenna is becoming more and more important.

Based on the traditional bow-tie antenna, this paper abandoned the resistive loading method that reduces radiation efficiency [5], and designed a tripod-shaped antenna through the structural loading method of the truncated arm, the end slot and adding reflector. HFSS is used as an optimization tool to realize the design of ultra-wideband antenna with anti-interference, good directivity and miniaturization.
2. Design scheme

In order to realize the detection of shallow underground pipelines, this paper proposes to design an UWB antenna of GPR with input impedance of 50 ohms and working bandwidth is about 0.5 GHz~2GHz.

2.1. Basic principle of traditional bow tie antenna

The traditional bow tie antenna plays an important role in the commercial GPR antenna because of its simple structure, convenient transformation and excellent performance. Therefore, the traditional bow tie antenna is chosen to be loaded with composite structure to meet the design objectives. The structure of traditional bow tie antenna is shown in Figure 1 [6].

The bow tie antenna can be regarded as a variant of biconical antenna, which is a plane form of biconical antenna. Then the output impedance of bow tie antenna can be calculated as shown in Formula 1 [3]:

\[ Z_c = 120 \ln \cot \frac{\theta}{4}, \]  

\( \theta \) is the antenna arm angle. It can be seen from the above formula that if the length of the antenna arm is constant, the larger the antenna opening angle, the wider the bandwidth, but the larger the size. In practical application, in order to consider the working bandwidth and antenna size, the antenna arm angle is usually designed to be 60 °. The design length of antenna arm is shown in formula 2 [6]:

\[ L = \frac{\lambda}{4} \left(1 - \frac{97.82}{Z_c}\right), \]  

\( \lambda \) is the wavelength of electromagnetic wave at antenna center frequency in air. According to the antenna demand and the convenience of subsequent processing, the center frequency of the original bow tie antenna is set as 500MHz, and the FR-4 epoxy resin base plate is used as the antenna substrate. Design the antenna arm length \( L = 80mm \) and antenna arm width \( W = 100mm \).

2.2. Research and design of the structure of tripod shaped UWB antenna

By truncating the antenna arm, the working bandwidth of antenna is increased and the miniaturization of the antenna is realized; The slot at the end of the antenna arm improves the current reflection at the end of antenna, thereby reducing the negative impact of reflected current on the radiation performance. The overall plan of the tripod antenna is shown in Figure 2.

In order to improve the antenna's directivity and anti-interference ability, a metal reflector is chosen instead of a metal shielded back cavity. This is because when a metal back cavity is used, the absorbing material inside the back cavity will seriously weaken the antenna's radiation performance at high frequencies. Using a metal reflector and selecting the appropriate height of the metal backplane can also improve the directivity and anti-interference ability without affecting the high frequency performance. The 3D structure of the designed tripod antenna is shown in Figure 3.
2.3. Simulation and optimization analysis of the structure of the tripod UWB antenna

This section analyzes the impact of the cutoff length of the antenna arm on the antenna operating bandwidth; The influence of the diameter of the opened circular slot and the height of the metal reflector on the working bandwidth and the degree of impedance matching.

Based on the original bow tie antenna, only the bottom of the antenna arm is cut off, so that the parameter $W_2$ is changed from 50mm to 90mm at a step interval of 10mm. Figure 4 shows the trend of the S11 curve of the antenna with the parameter $W_2$:

As can be seen from Figure 4, the truncation at the bottom of antenna arm makes operating frequency shift to a higher frequency. When $W_2 = 70$mm, S11 has the best gain value; while $W_2 = 90$mm, although S11 gain value is slightly lower, the effective bandwidth is the widest, and the overall performance is the best. At this time, compared with the original bowtie antenna, the 0.5GHz ~ 0.54GHz operating bandwidth is widened to 0.6GHz ~ 1.4GHz.

The following analysis when $W_2 = 90$mm, only cut off top of the antenna to change parameter $W_1$ from 10mm to 50mm at 10mm step intervals. Figure 5 shows the trend of the antenna's S11 curve with the parameter $W_1$:
Figure 5. S11 curves of antennas at different W1 lengths.

It can be seen from Figure 5 that the truncation at the top of antenna arm makes the antenna's operating frequency continue to migrate to high frequencies. When the top of the antenna is truncated to the parameter $W_1 = 50\text{mm}$, the bandwidth and gain of the antenna $S_{11}$ will definitely reach the best. At this time, the working bandwidth of antenna is widened to $710\text{MHz} \sim 1.8\text{GHz}$.

Optimizing only by the method of loading with a truncated arm will make the reflected current at the end of antenna more chaotic, reduce the degree of impedance matching, and damage radiation performance of antenna. Therefore, a semi-circular groove is formed at the end of antenna arm to reduce reflected current and improve current distribution on antenna arm. Keep $W_1 = 50\text{mm}$ and $W_2 = 90\text{mm}$. Analyze the semicircular groove radius $R_{\text{cut}}$ at the end of the antenna arm and how it affects $S_{11}$ curve. $R_{\text{cut}}$ increased from $25\text{mm}$ to $45\text{mm}$ in $5\text{mm}$ step intervals. The effects of $R_{\text{cut}}$ on the antenna's $S_{11}$ and output impedance are shown in Figures 6 and 7, respectively:

Figure 6. S11 of the antenna at different $R_{\text{cut}}$ lengths.

Figure 7. Real part of impedance (left) and imaginary part (right) for different $R_{\text{cut}}$ lengths.
It can be seen from Figure 6 that after the semi-circular groove is opened at the end of the antenna, the center frequency shifts to higher frequency, and S11 bandwidth is also slightly reduced. The working bandwidth is the widest when $R_{\text{cut}} = 25\text{mm}$. To achieve antenna output impedance matching, it is necessary to make the equivalent impedance of antenna as stable as possible at the coaxial RF cable 50ohms. It can be seen from Figure 7 that when $R_{\text{cut}} = 25\text{mm}$, the real part of the antenna impedance is most uniformly distributed around 50ohms, and the imaginary part of the impedance is closer to 0ohm. Therefore, the parameter $R_{\text{cut}} = 25\text{mm}$ is selected, and the working bandwidth of antenna is $750\text{MHz} \sim 1.85\text{GHz}$.

At this time, the tripod antenna is still an omnidirectional radiation antenna. In order to meet the directivity requirements of GPR system, a metal reflection plate should be added behind the tripod antenna. When the distance between the reflection plate and the antenna is appropriate, not only the anti-interference ability of the antenna can be improved, but also the directivity and gain of the antenna can be improved due to the mirror image effect. Analyze the change trend of the antenna S11 when the height $h$ of the reflector is 10 mm in steps and the increment value is 140 mm from 100 mm. The simulation results are shown in Figure 8:

![Figure 8. S11 curves of antennas at different h heights.](image)

It can be seen from FIG. 8 that at $h = 100\text{mm}$, the antenna S11 curve has the widest working bandwidth at -10dB, reaching $700\text{MHz} \sim 2\text{GHz}$, basically achieving the antenna operating frequency design target, and the relative bandwidth reaching 96%, which meets the ultra-wideband antenna standard. The antenna's directivity is reflected in the next section.

3. Optimized tripod UWB antenna

After the design of the truncated arm, the slot, the reflection plate and the optimization of the HFSS simulation, the antenna arm width of the tripod antenna $W_1 = 50\text{mm}$, $W_2 = 90\text{mm}$, the antenna arm length $L_1 = 24\text{mm}$, $L_2 = 64\text{mm}$, and the height of the reflection plate $h = 100\text{mm}$. The basic structural parameters of the reflector-based ultra-wideband tripod-shaped antenna that can be applied to practical engineering are shown in Table 1:

The working bandwidth and direction characteristics of the designed tripod-shaped UWB antenna are shown in Figures 9 and 10, respectively:

![Figure 9. Operating bandwidth S11 under -10dB.](image)

It can be seen from Figure 9 that the operating bandwidth of S11 under -10dB is $0.7\text{GHz} \sim 2\text{GHz}$, and the best radiation performance is $0.85\text{GHz}$, $1.3\text{GHz}$ and $1.8\text{GHz}$ respectively, and the relative bandwidth is as high as 96%. And the HFSS simulation results are shown in the operating bandwidth VSWR (Voltage Standing Wave Ratio) $<2$, it is an ultra-broadband antenna with excellent transceiver performance.
Table 1. Basic structure parameters of tripod antenna.

| Design variable name                  | Parameter value |
|---------------------------------------|-----------------|
| Length of antenna arm L1              | 24mm            |
| Length of antenna arm L2              | 64mm            |
| Width of antenna arm W1               | 50mm            |
| Width of antenna arm W2               | 90mm            |
| Antenna semicircle groove radius R_cut/2 | 25 mm         |
| Square feed port spacing L_Port       | 4mm             |
| Dielectric constant of antenna substrate $e_r$ | 4.4           |
| Dielectric constant of antenna substrate sub_X | 150mm         |
| Length of antenna substrate sub_Y     | 250mm           |
| Thickness of antenna substrate sub_H  | 1.6mm           |
| Height of metal reflector h           | 100mm           |

Figure 9. S11 curve (left) VSWR curve (right) of UWB antenna.

The three-dimensional radiation pattern of the antenna is obtained by HFSS simulation, which is shown in Figure 10. It can be seen that the radiation direction of the antenna changes from omnidirectional radiation to directional radiation under the effect of the reflector on the E-plane, while the H-plane is omnidirectional radiation in the entire operating bandwidth. It can be seen from the E-plane and H-plane patterns that the width of the radiation main lobe is above 100 degrees, and the radiation characteristics are good.

4. Conclusion
This paper designs a miniaturized tripod-shaped ultra-wideband antenna for GPR based on bow tie antenna. The design of the original bow tie antenna was researched by truncating the antenna arm, cutting a round slot at end of antenna, and adding a metal reflector behind antenna.
After HFSS parameter optimization and simulation, the working bandwidth of antenna has been expanded from 0.5GHz to 0.54GHz to 0.7GHz to 2GHz, and the relative bandwidth is as high as 96%. The antenna input impedance is 50ohms, which can be perfectly matched with the RF coaxial cable; the width of the radiation main lobe is more than 100 degrees, and the radiation direction characteristics are good. This paper provides an ultra-wideband antenna with good performance for GPR for shallow underground pipeline detection.

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