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LETTER

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Using end reflections to improve the pulse radiation efficiency of bow-tie antenna

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Abstract: Bow-tie antenna is widely used for pulse radiation, but the radiation efficiency is less than 30%. In this letter, a novel method is presented to improve the efficiency by exploiting the energy in end reflections, which are thought to be harmful and usually suppressed in the reported literatures. When the exciting pulse is bipolar and monocycle, it is indicated that, the end reflection can be used for producing a pulse with increased peak value by optimizing the antenna length. The simulation results show that the pulse radiation efficiency can be increased 100% with the presented method.

Keywords: bow-tie antenna, radiation efficiency, pulse, ground penetrating radar (GPR), ultra wide band (UWB)

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Bow-tie antenna has been widely used for pulse radiation in impulse ground penetrating radar (GPR) [1], but the radiation efficiency is very low. The radiated pulse consists of main pulse and end reflection [2]. Main pulse is the only part can be used for probing objects, while end reflection can mask object reflections and should be suppressed by absorbing [3, 4]. From the viewpoint of probing objects, therefore, the antenna radiation efficiency of impulse GPR can be indicated by the peak value of the main pulse. It has been proved that, the energy of main pulse is less than 30% of the whole radiated energy [3]. Some efforts have been devoted to improve radiation efficiency by increasing the energy fed into the antenna [5], or decreasing the dissipated energy in suppression [3, 4], which attracts the most attention. However, a more promising method should be exploiting the considerable energy in end reflections, which is rarely reported in literatures. Lestari's design [4, 6] can be considered to belong to this category. But the radiation is optimized according to the central frequency of the exciting pulse, which is always of ultra wide band (UWB). Therefore, Lestari's optimization need to be improved, though he validated his method by simulated and measured results. In this letter, we present a novel method to improve the pulse radiation efficiency of bow-tie antenna in time domain by using the energy in end reflections. Our studies include selecting the exciting pulse and optimizing the antenna length.

2 Bow-tie antenna

2.1 Antenna geometry

For pulse radiation, it is better to choose a circular-end bow-tie antenna rather than a straight-end one. Fig. 1 shows the geometry of a common circular-end bow-tie antenna, which is determined by three parameters, the arm length L, the flare angle θ, and the gap distance g. L is closely related to the radiation efficiency, and will be optimized for pulse radiation in this letter. Here we keep $\theta = 60°$, and $g = 1\,\text{mm}$, since we want to study the radiation efficiency.

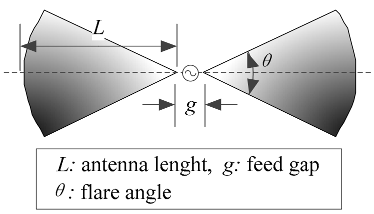

Fig. 1. The geometry of bow-tie antenna.

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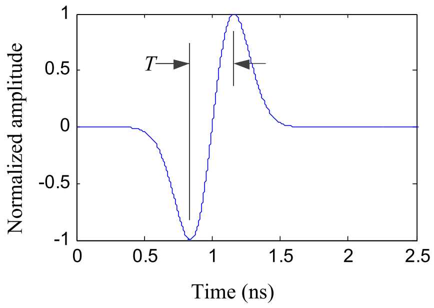
2.2 Exciting pulse

Usually, the exciting pulse of impulse GPR is bipolar and monocycle, such as the Ricker pulse (the first derivative of the Gaussian pulse)

$$s(t) = 2\pi f_c\sqrt{e}(t - t_0)e^{-2\pi^2 f_c^2 (t-t_0)^2} \tag{1}$$

where f_c is the center frequency and t_0 is the time-shifting factor. Fig. 2 shows a Ricker pulse with a central frequency $f_c = 1\,\text{GHz}$. As we know, a bipolar pulse only has a small amount of direct and low-frequency components, which are difficult to be radiated by antenna. And this is the traditional reason of



(a) Wave form. **(b)** Spectrum.

Fig. 2. A Ricker pulse with a central frequency $f_c = 1\,\text{GHz}$, T is the time interval between the positive and negative peaks.

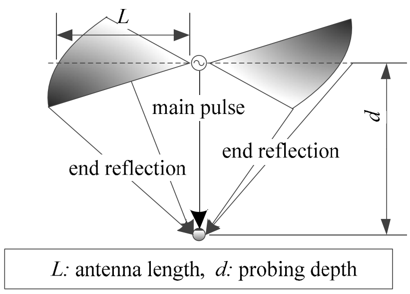


Fig. 3. Radiation composition in space.

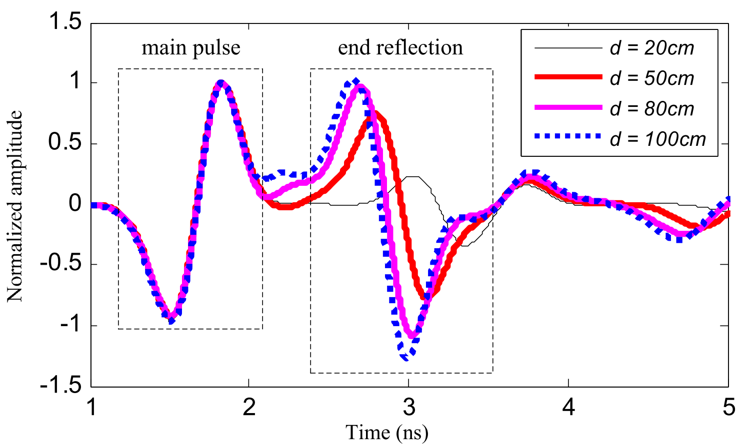


Fig. 4. Radiated pulses of a bow-tie antenna with $L = 30\,\text{cm}$.

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choosing bipolar pulse as the exciting pulse. In this letter, we will show the meaning of bipolar exciting pulse from the viewpoint of improving radiation efficiency of antenna.

3 Improve the pulse radiation efficiency

3.1 Pulse radiation of bow-tie antenna

The radiation of a bow-tie antenna is mainly from the superposition of the main pulse that is the direct radiation from the feed, and the end reflections that are strong diffractions from the two ends. Fig. 3 depicts the spatial composition of the radiated pulse in the broadside direction of the antenna, where d is the probing depth in the broadside direction. In GPR applications, we are mainly interested in the radiation in the broadside direction of an antenna.

When a bow-tie antenna is long enough, the main pulse and end reflection can be separated from the radiated pulse. Fig. 4 shows the normalized transmitted waveforms in different probing depth of a bow-tie antenna with $L = 30\,\text{cm}$. The antenna is excited by a Ricker pulse with a central frequency of 1 GHz, as shown in Fig. 2. It can be found that the energy in end reflections is very remarkable. As the distance increases, the end reflections grow stronger, and they become even stronger than the main pulse in a large probing depth. It can be found that, the pulse radiation efficiency will be significantly improved if the energy of end reflection is utilized rather than dissipated by resistors during suppressing.

3.2 Exploiting the energy of end reflections

From Fig. 4, we can also observe that, the waveforms of the main pulse and the end reflection are similar, but their phases are inverse. And the second peak of the main pulse is in the same polarity as the first peak of the end reflection. The interval between these two peaks is determined by the antenna length and the probing depth. For a given probing depth d, it means that, there is an optimal antenna length L_o, in which these two peaks will appear at the same time. And a superposed pulse with increased amplitude will be produced, which means the pulse radiation efficiency is improved. As long as the exciting pulse is bipolar and monocyclic, the optimal antenna length will exists. And this is the meaning of bipolar exciting pulse for improving radiation efficiency of antenna. In the broadside direction, L_o satisfies the following equation according to the geometry in Fig. 3

$$\frac{\sqrt{d^2 + L_o^2} - d + L_o}{c} = T \tag{2}$$

where T is the time interval between the positive and negative peaks of exciting pulse, as shown in Fig. 2, and c is the propagation velocity of electromagnetic wave in free space. Therefore,

$$L_o = \frac{cT(2d + cT)}{2(d + cT)} \tag{3}$$

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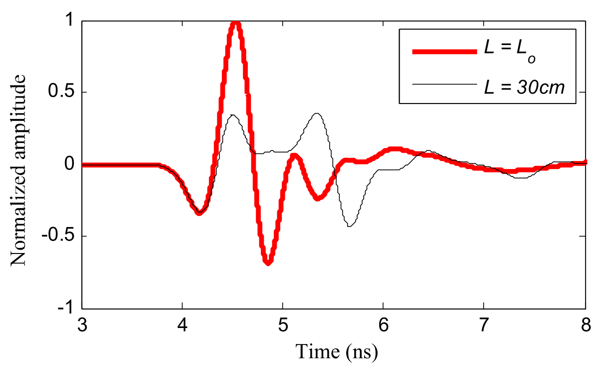
In the free space, the optimal antenna length is related to the probing depth and the exciting pulse. But when $d \gg cT$, which is usually satisfied in practical GPR applications, $L_o \approx cT \triangleq L'_o$.

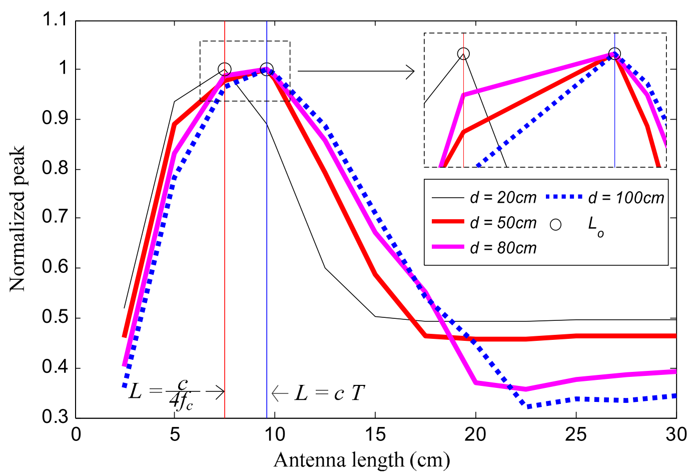
4 Experiment results and discussion

The presented method is tested by simulation experiment. In the simulation, we use the algorithm of finite difference time domain (FDTD) to calculate the radiated pulse of bow-tie antenna. The exciting pulse is a Ricker pulse with a central frequency $f_c = 1\,\text{GHz}$, as displayed in Fig. 2.

Fig. 5 (a) shows the comparison results of pulses radiated by an antenna with $L = 30\,\text{cm}$ and an antenna with the optimal length. The probing depth is $d = 100\,\text{cm}$. It can be seen that, the peak of the superposed pulse is remarkably increased after the antenna length is optimized. Now the superposed pulse can be defined as the main pulse, which can be used for probing objects. And the radiated pulse excluding the new main pulse is called as the end reflection. Increased peak of the main pulse not only means higher pulse radiation efficiency but also lower end reflection, which is very important for object detection. However, an inevitable fact is that the superposed pulse is expanded. When the desired frequency is not too high, it is feasible to solve this problem by narrowing the exciting pulse to meet the demand of



(a) The waveforms of the radiated pulses when $d = 100\text{cm}$.



(b) Normalized peak value when antenna length changing.

Fig. 5. Simulation results.

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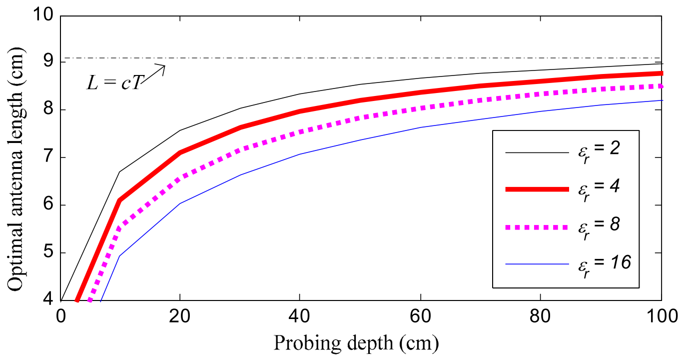

Fig. 6. Optimal antenna length with ground concerned.

frequency band.

Fig. 5 (b) shows the relationship between the peak value of main pulse and the antenna length. We can find that the radiation efficiency of antenna in its optimal length is the highest. And the highest radiation efficiency is increased nearly 100% to that of antenna with length larger than 20 cm. When d is larger than 50 cm, Fig. 5 (b) also shows that the optimal length can be approximated to cT, where $T = 1/(\pi f_c)$ for a Ricker pulse.

Additionally, the suggested length by Lestari [4], which is $c/4f_c$, is also marked on Fig. 5 (b). It is shown that, the performance of our method is slightly better than Lestari's. But when the probing depth is small, for example 20 cm in the simulation, the length $c/4f_c$ is more suitable than L'_o, since $c/4f_c$ is closer to L_o at this moment. What's more, Lestari derived the optimal length by optimizing the radiation of the central frequency of the exciting pulse, which is not sufficient to optimize the radiation of a UWB pulse. So we think our derivation of the optimal antenna length is more convincible.

Bow-tie antenna is usually printed on the substrate. But the substrate can only affect a slight reduction in the size of the antenna, as long as the substrate is not too thick and the permittivity is not too high.

The lossy ground influences the performance of the antenna closing to it. We find that the ground will only slightly affect the propagation velocity of surface current on the antenna, when the antenna height is larger than 1 cm. If the relative permittivity of the ground is ε_r, then

$$L_o = \frac{\sqrt{\varepsilon_r}\sqrt{d^2 + c^2T^2 + 2dcT\sqrt{\varepsilon_r}} - cT - d\sqrt{\varepsilon_r}}{\varepsilon_r - 1} \tag{4}$$

Fig. 6 shows the optimal antenna length in four kinds of ground. The ground with large permittivity can slightly decrease the optimal length. And the optimal length also approximates to cT, as the probing depth increases.

5 Conclusions

Nearly 70% of the energy fed into a bow-tie antenna is radiated as the form of end reflection, which causes low radiating efficiency of bow-tie antenna. But if a bow-tie antenna is excited by a bipolar pulse, the pulse radiation efficiency

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can be significantly improved by utilizing the remarkable energy in end reflections. In this paper, we enhance the pulse radiating efficiency by merging the main pulse and end reflection. For relatively large probing depth, the simulation results show that the pulse radiation efficiency of the bow-tie antenna in its optimal length is more than 200% to that in infinite length. Our design is especially useful for a low-frequency GPR application, in which the pulse radiation efficiency is very crucial.

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