This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Voipio, Veli-Erkki

The Gopher Antenna - A New Efficient Design for Ground Penetrating Radar

Published in:
International Workshop on Advanced Ground Penetrating Radar

DOI:
[10.3997/2214-4609.201902586](https://doi.org/10.3997/2214-4609.201902586)

Published: 01/01/2019

Document Version
Peer reviewed version

Published under the following license:
Unspecified

Please cite the original version:
Voipio, V-E. (2019). The Gopher Antenna - A New Efficient Design for Ground Penetrating Radar. In *International Workshop on Advanced Ground Penetrating Radar* (Proceedings). European Association of Geoscientists and Engineers (EAGE). <https://doi.org/10.3997/2214-4609.201902586>

The Gopher antenna: A new efficient design for ground penetrating radar

Veli Voipio

Department of Electronics and Nanoengineering, Aalto University

Espoo, Finland

veli-erkki.voipio@aalto.fi

Abstract—In this article, we propose a new design we call the “Gopher antenna”: a patch antenna structure which does not require a resistive load and is therefore more efficient than the current ground-penetrating radar (GPR) antennas. When tested, it works well in a GPR application as low as approximately -25 dB of the application’s original transmit power. The Gopher antenna also meets the general requirements for the GPR antennas: a received wide spectrum and a good impulse response. Departing from the common designs (bow-tie dipoles and horn/Vivaldi structures), the Gopher antenna is a patch-antenna structure consisting of a quarter-wave feeder and a parasitic half-wave patch with no resistive load. The Gopher antenna has a directive radiation pattern, a good impulse response without distortion, a reasonable cross-polarization ratio, and a good radiated spectrum also when placed on the ground.

Keywords— Antennas, GPR, Ground penetrating Radar, Patch antenna, UWB

I. INTRODUCTION

Ground-penetrating radar is a non-destructive, electromagnetic investigative tool used widely in many fields, including geophysics, civil engineering, and archaeology. Recent descriptions of GPR can be seen in [1], [2] and [3]. Currently the most common system is an impulse radar employing a quasi-bistatic antenna configuration. The ground-coupled antenna (proximal operation) is a common setup, mostly employing bowtie antennas [4].

For several decades, much research has been devoted to ground-penetrating radar (GPR), with many authors emphasizing the need for innovative antenna technology [1]. Currently, most of the antenna designs utilize a resistive load to achieve the desired characteristics. However, this significantly reduces their efficiency [5]. To improve the efficiency, we here propose a design which is constructed without any resistive load in the antenna structure. As an additional bonus, the antenna is also more directive than these previous approaches. Consequently, our design can increase the depth of penetration. Furthermore, this approach provides higher front-to-back ratio, thus avoiding the need for additional shielding. Although larger than most commercial antennas, our design results in a total setup comparable in size to most other GPR systems.

For GPR, the wave is expected to penetrate vertically deep into the ground as a TEM wave. The received time-domain signal is digitized and stored, possibly with increasing amplification along the depth. To reduce interference and noise, the data can be post-processed in a computer with filtering. Other methods, such as migration [5] or tomography [6] can be used to extract features under the ground.

Ground-penetrating radars require wide-bandwidth antennas, a frequency response ranging between as low as

nearly direct current and higher, and a good impulse response. To meet these requirements, this study applies patch antenna technology to develop an antenna that offers greater simplicity and directivity (gain) than that provided in current designs. In this work, the efficiency is improved by avoiding the use of lossy materials or resistive components. The wide bandwidth for this antenna is partly a result of intentional impedance mismatch in the lowest frequency region (see section III.B), which adds its own losses, but those losses can be regarded as part of the necessary filtering losses to achieve the desired pulse shape.

The finite-difference time-domain method (FDTD) was used for the simulations. The FDTD simulations were done using Matlab[®] with the code from [7], adapted by the author. A current comparison of the time-domain methods used for GPR can be found in [8]. A vector network analyzer (VNA) was used for the antenna measurements in both the laboratory and the field. Antennas in the face-to-face position were used in the simulations and measurements to provide information on the pulse shape and the radiated spectrum for the GPR. This study will not focus on the usual impedance bandwidth nor far-field radiation pattern aspects due to the near-field effects of the GPR application.

The rest of this paper is organized as follows: Section 2 describes the antenna, Section 3 evaluates the performance and makes some design comparisons. Section 4 presents results from the practical outdoor measurements validating the design.

II. THE GOPHER ANTENNA

The proposed antenna is comprised of two parts: (1) the feeder antenna and (2) a parasitic half-wave patch element (Fig. 1). The feeder antenna (i.e., driven element or radiating feed) is a quarter-wave monopole L-shaped antenna which is intentionally mismatched at its lowest resonant mode to achieve a wide bandwidth (see section III.B), and one of its higher resonant modes (3 x lowest) is matched to the feed impedance. The parasitic half-wave patch element [9] (coplanar element) has its lowest resonant frequency tuned to near the 2 x lowest frequency of the feeder element and coupled with it in order to provide a dual-resonant structure to increase the bandwidth. The phasing allows the structure to form a two-element antenna array. The directivity of this array is slanted in order to give optimal performance in a bistatic radar. The antenna could also be described as a resonator-loaded antenna. To the author’s knowledge, no studies have presented similar antennas, although the general design principles are not new.

In this study, some well-known design principles for the wide-band antennas were utilized. First, a thick substrate (of air in this case) was used as the bandwidth is known to increase with the substrate thickness. Secondly, that the impedance bandwidth can be increased with the help of

multi-resonance matching. The third principle is to locate the feed and the resonator sequentially, as shown in Fig. 1, in order to expand the radius of the radiation hemisphere relative to the center frequency. The distributed fields of the reactive coupling and the size and position of the elements affect each other in a complex way, thus the final optimizing was done by experimenting in simulations.

Such a structure (although simpler) was previously used by the author in telecom antenna simulations (Unpublished) and later noted that it provides a satisfactory impulse response for the GPR antenna. Then it was intriguing to analyze why it functions in such a way, and the first results and applications are presented here.

Fig. 1. Gopher antenna structure drawing with dimensions. Material is copper plate 0.5 mm. In FDTD simulations the perfect electric conductor was used as material.

In order to have a short name for this antenna design, we suggest “Gopher antenna”. The name describes the ground penetration enabled by the design. Furthermore, the gopher’s incisor teeth resemble the antenna’s structure.

For a size comparison, a picture of the internal structure of one comparable commercial antenna can be seen in [8]. Assuming that the information in [10] is about the same antenna, the horizontal dimensions of the box of the 1.2 GHz commercial antenna are about half of the Gopher antenna’s dimensions. On the other hand, the front-to-back-ratio of the Gopher antenna is so good that additional shielding does not contribute to its total size.

III. SIMULATED AND MEASURED PERFORMANCE

A. Gopher antenna in face-to-face setup

Face-to-face testing for the impulse response is commonly used for the GPR antennas, as in [5]. The antennas are connected to the vector network analyzer to measure the S_{21} , or the value is calculated using FDTD simulations. The ground plates are parallel and the antennas are in a mirrored position. A distance 600 mm was used between the ground plates. Simulated results are seen in Fig. 2 and Fig. 3, and measured in Fig. 4.

Fig. 2. Simulation results in a face-to-face setting: excitation voltage and received current face-to-face impulses (the peak to next ratio is 1.36).

In [5], the Ricker wavelet (Ricker pulse, second derivative of the Gaussian distribution) has been proposed as an ideal pulse for the GPR. The actual received pulse can vary for various reasons, including distance, medium, angle, target, and excitation pulse. For a detailed discussion of the concept of time sidelobes and ring-down and dispersion the reader is referred to [5] and [11]. The peak-to-next ratio of the received pulse is used here as a simple goodness of fit. It is calculated of the absolute value of highest peak in the received signal divided by the absolute value of the next highest peak beside it (these peaks have opposite signs). If the transmit pulse is a second derivative Gaussian (Ricker) pulse, then ideally the received pulse is fourth derivative Gaussian, which has a peak-to-next ratio of 1.67. As in Fig. 2, a reasonably good value 1.36 is achieved. Also the ringing is low.

The simulated transfer spectrum in Fig. 3 is calculated dividing the received spectrum by the transmitted spectrum, which corresponds to the deconvolution of received pulse with the transmitted pulse in the time domain. In Fig. 3 the spectrum is 423–2142 MHz at the -10dB limit. Thus the simulated bandwidth ratio is 5.1.

The transfer spectrum in Fig. 4 was obtained using the vector network analyzer (VNA) from the S_{21} measurement in face-to-face configuration with identical antennas. The measurement shows the gain of the antenna versus frequency in that single direction and polarization, same as in the simulation. The limit of -10dB below the maximal power is used to define the bandwidth limit of the single antenna.

Fig. 3. Simulation results in a face-to-face setting in the air at a 600mm distance: transfer spectrum (bandwidth ratio is 5.1)

Fig. 4. Measured S_{21} transfer spectrum: face-to-face setting in the air at a 600 mm distance (bandwidth ratio is 4.9)

In Fig. 4, the spectrum is 366–1776 MHz at the -10dB limit. Thus the measured bandwidth ratio is 4.9 which is approximately same as the simulated bandwidth in Fig. 3. This bandwidth ratio well exceeds the minimum requirement octave mentioned in [12]. Calculating the fractional bandwidth with the equation (4.7) in [5] the result is $BW=2 \cdot (f_H - f_L) / (f_H + f_L) = 132\%$.

One example of a commercial antenna is in [13]. It has a spectrum of 850–3650 MHz, thus the bandwidth ratio is 4.3 and the fractional bandwidth is 125%: roughly the same magnitude as in the Gopher antenna, but the line top is flatter and thus better in the commercial antenna. Further comparison is in section III.D.

B. Impedance characteristics of the Gopher antenna

A dual resonance is visible in Fig. 5(a)–(b) in the 1500 MHz area. The lowest resonant mode is at 500 MHz in the feeder element. At the lower end, between 0.5 and 1.0 GHz a low antenna impedance was needed as trade-off to the optimal impedance in order to achieve a suitable radiated bandwidth in that low frequency region (if the feed impedance is higher than the impedance of the load serial resonator, the bandwidth will increase). The field measurements of the antenna impedance in Fig. 6 conform to the FDTD simulations in Fig. 5 reasonably well.

Fig. 5. Simulated input impedance (a) on the Smith chart, (b) reflection coefficient.

Fig. 6. Field measurement of the input impedance in air (a) on the Smith chart (b) reflection coefficient.

C. Radiation pattern: preliminary remarks

The radiation pattern of a patch antenna is directive, and the combination of the feeder and the patch produce a two-element array. The impulse radiation pattern in the ground depends on the transmitted impulse, the permittivity of the ground and the distance to the target. The snapshot of a simulated impulse radiation in Fig. 7 indicates that the pattern is slanted. The antenna pair should be positioned so that the reflected wave travels optimally to the receiving antenna, which will be a subject of a future study.

The antenna directivity is a function of the frequency and thus works as a part of the filtering effect in the main beam direction, and is considered here as an advantage. The ground plate functions as a reflector towards the ground for all frequencies and as well as a shield upwards. The cross-polarization ratio is reasonable, particularly in the boresight direction, similar as in the square patch antennas generally.

Fig. 7. Snapshot of a simulation in the face-to-face case: magnitude of E-field showing the slanted radiation in the air

D. Performance of comparable antennas

The current commercial technology utilizes mostly bow-tie dipoles with resistive load to achieve sufficient bandwidth and good impulse shape, but the resistive load reduces their efficiency: “For a resistively loaded antenna of the Wu-King type, the efficiency is approximately 10% but rises to a maximum of 40% for antenna lengths of 40λ ” [5]. Their directivity is of the same magnitude as the ordinary dipoles. Their impedance matching is appropriate along the spectrum. The Gopher antenna is efficient (no lossy materials nor resistive elements: practically no dissipation) and directive, but it is difficult to compare the Gopher antenna to commercial antennas since data about them is not publicly

available, and these antennas are usually sold in an integrated package with the electronics.

Generally, the loaded dipole operates at 20% efficiency (-7dB) and its gain is 3 dBi, totaling -4 dBi. Gopher antenna operates at about 100% efficiency and almost 10 dBi gain; thus, the difference is 14 dB for the antenna and 28 dB for the antenna pair. Therefore, only a small transmit power is needed with the Gopher antenna pair in order to receive a sufficient input signal, as demonstrated in the next section.

IV. A. FIELD-TESTING THE ANTENNA IN A GPR DEVICE

This section contains a short description of two types of field measurements to show how the Gopher antenna works in use. The results are repeatable and reveal structures underground.

A. Field-testing the antenna in a GPR device

To validate the antenna behavior in actual use, this test utilized a low-cost commercial GPR electronics from Easy Radar USA. The transmitter sends a Gaussian impulse of 2 ns with an 8 V peak to a 50 Ω dummy load. Currently, only a small part (-25 dB) of the impulse power is directed to the Gopher antenna. Fig. 8 shows a GPR slice when the transmit power is 3.4 mW.

This measurement profile was recorded in a lake towards the beach. There is no clutter in the water (except for a chain visible on the left side of the picture). The inbuilt simple adaptive filtering of the radar data acquisition software was in use. The muddy bottom, and the steep rock shore can be seen in the picture. There are also internal and external reflections visible as horizontal lines, and also some interference and noise. Due to the antenna directivity, the hyperbolas are minimal, and a steep slope on the right is clearly visible. The relative permittivity $\epsilon_r \approx 81$, the two-way time is 100 ns, thus the depth scale is about 1.7 m.

When measured from the bottom reflection in Fig. 8 the wavelength is 6 cm which corresponds to the 500 MHz wavelength in water. According to [12], the typical maximal depths of penetration rarely exceed 20 wavelengths. Here the maximal achieved depth is approximately 1.3 m which is slightly over 20 wavelengths. Thus, we can infer that a very low transmit power is indeed sufficient.

Fig. 8. GPR slice showing the bottom of the lake, the horizontal axis is approximately 3 m

V. CONCLUSION

In this paper we presented a new “Gopher” antenna structure, simulations and measurements. The FDTD simulations demonstrate that the antenna meets the requirements for a GPR antenna in bandwidth and impulse shape. The antenna measurements are in line of the simulations. The GPR system performance with the antenna attached was verified in the field tests.

The Gopher antenna does not have resistive losses as most commercial GPR antennas do. It is also directive. It works well in a GPR application with approximately 25 dB below the application’s original transmit power. The low transmit power reduces interference and thus may allow an accurate positioning receiver installed on top the antenna box with a wireless remote control. We expect that this antenna structure will form a basis for new commercial GPR antenna developments.

ACKNOWLEDGMENT

Easy Radar USA (Chief Engineer Karl Harrar) and GeoBlast Finland (Dr. Tero Hokkanen). At Aalto University: Research Engineer Matti Vaaja and Associate Professor Ville Viikari

REFERENCES

- [1] A. Benedetto and L. Pajewski, *Civil Engineering Applications of Ground Penetrating Radar*, Heidelberg, Switzerland: Springer, 2015.
- [2] D. Goodman and S. Piro, *GPR Remote Sensing in Archaeology*, Heidelberg: Springer, 2013.
- [3] L. Conyers, *Ground-Penetrating Radar for Archaeology*, Plymouth UK: AltaMira Press, 2013.
- [4] E. Uzi, *Ground Penetrating Radar Theory and Practice*, Oxford: Elsevier, 2017.
- [5] H. Jol, *Ground Penetrating Radar: Theory and applications*, Oxford: Elsevier Science, 2009.
- [6] R. Persico, *Introduction to Ground Penetrating Radar: Inverse Scattering and Data Processing*, Hoboken, NJ: Wiley, 2014.
- [7] A. Elsherbeni and D. Veysel, *The Finite-Difference Time-Domain method for Electromagnetics with MATLAB Simulations*, Raleigh NC: SciTech Publishing Inc., 2008.
- [8] C. Warren, L. Pajewski, D. Poljak, A. Ventura, A. Giannopoulos and S. Sesnic, “A comparison of finite-difference, finite-integration, and integral-equation methods in the time-domain for modelling ground penetrating radar antennas,” *ICGPR*, Hong Kong, 2016.
- [9] J. Ollikainen, *Design and Implementation Techniques of Wideband Mobile Communications Antennas*, Espoo: HUT Radio Laboratory, 2004.
- [10] C. Warren and A. Giannopoulos, “Creating FDTD models of commercial GPR antennas using Taguchi’s optimisation method,” *Geophysics*, Vol. 76, nr 2, pp. 37-47, 2011.
- [11] H. Scharf, *The Art and Science of Ultrawideband Antennas*, 2nd edition, Boston: Artech House, 2015.
- [12] D. Daniels, *Surface-Penetrating Radar*, London: IEE, 1996.
- [13] A. Akdagli, “Behaviour of Electromagnetic Waves in Different Media and Structures,” *Intech*, 2011. [Online]. Available: <http://www.intechopen.com/books/behavior-of-electromagnetic-waves-in-different-media-and-structures/detection-of-delamination-in-wall-paintings-by-ground-penetrating-radar1>. [Retrieved Feb 15 2017].