Vivaldi Antenna for RF Energy Harvesting

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Abstract. *Energy harvesting is a future technology for capturing ambient energy from the environment to be recycled to feed low-power devices. A planar antipodal Vivaldi antenna is presented for gathering energy from GSM, WLAN, UMTS and related applications. The designed antenna has the potential to be used in energy harvesting systems. Moreover, the antenna is suitable for UWB applications, because it operates according to FCC regulations (3.1–10.6 GHz). The designed antenna is printed on ARLON 600 substrate and operates in frequency band from 0.810 GHz up to more than 12 GHz. Experimental results show good conformity with simulated performance.*

Keywords

RF energy harvesting, UWB, Vivaldi antenna

1. Introduction

Energy harvesting is a functionality which generates a small amount of electrical power. Harvested energy from the environment can be reused to operate low-power electronic devices [2]. Waste energy could be harvested from light, heat, vibrations, radio waves etc. Only the radio-frequency (RF) harvesting is discussed in this paper.

RF energy harvesting is a promising technology that can benefit from billions of radio transmitters around the world. Radio transmitters including mobile telephones, handheld radios, mobile base stations and television/radio broadcast stations are potential sources of RF energy [1].

A basic energy harvesting system consists of a receiving antenna and a rectification circuitry. The block diagram of an energy harvesting system is shown in Fig. 1 [3]. An efficient harvesting of RF energy requires an efficient antenna. The antenna gathers the RF energy from environment. Subsequently, the rectifier circuit converts the received RF signal into DC signal. The matching circuit provides efficient and matched transmission between the antenna and a RF-DC converter. The desired values of voltage are converted by a DC-DC converter. The required voltage gets to the load through the charging circuit.
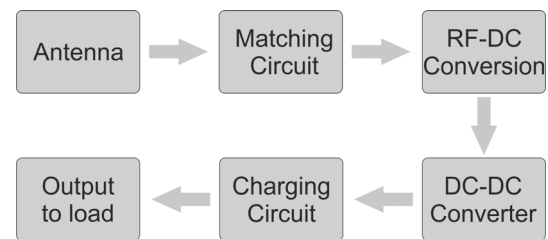

Fig. 1. Block diagram of the energy harvesting system.

The antennas for energy harvesting may be divided into several categories by the operating frequency band. The 900 MHz slot-dipole antenna on a flexible substrate was discussed in [4]. In [5], the slot-dipole antenna was improved and integrated with energy harvesting circuit. Due to the narrow-band operation and the directive radiation, the slot-dipole antenna harvests energy from one source only.

In [6], a triple-band antenna combining three planar monopoles was introduced. Monopoles were tuned to 940 MHz, 1.95 GHz and 2.44 GHz. That way, RF energy from three different bands was able to be harvested. In [7], an equivalent concept is applied to dual-band harvesting.

Wideband antennas for energy harvesting have been published in [8] to [10]. Antennas were conceived as a fractal monopole [8], and wideband monopoles [9], [10].

Antennas for energy harvesting must satisfy a number of requirements. Antennas operating at desired frequencies and polarization are necessary. Preferred antennas are those that cover larger frequency bandwidth.

Special attention should be turned to UWB (Ultra Wide Band) antennas which could harvest energy from as wide frequency band as possible. Also, simple fabrication, low cost and practical usability of antennas should be considered. To meet the conditions, an antipodal Vivaldi antenna was selected for the purpose of this work. Even though the Vivaldi antenna is not omnidirectional, but wideband, it could harvest energy from a half-space where there are multiple wireless communications technologies.

In the open literature, exploitation of Vivaldi-like antennas in harvesting systems has been described [15]: the Vivaldi concept was applied to an amorphous silicon solar Vivaldi harvester.

Similar design concepts of the Vivaldi antenna are presented in [16], where a novel compact end-fire antipodal Vivaldi antenna with bandwidth from 2 GHz to more than 12 GHz is proposed for ultra-wideband (UWB) applications e.g. radars, microwave imaging and in high data rate wireless systems. The antenna is proposed with bending microstrip line feed. The exponential slot of the proposed antenna is replaced by a sinusoidal modulated Gaussian tapered slot to improve the electrical length of the slot and to achieve a compact model of the antenna. Furthermore, in [17] the modified Compact Antipodal Vivaldi Antenna for 4–50-GHz UWB applications is also presented. The paper presents two different loading structures – circular-shape-load and slot-load, where mentioned loads can dramatically improve the impedance bandwidth and achieve compact geometry. A simulated dual Vivaldi nano-antenna with infrared frequency bandwidth and high radiation efficiency for photonic applications is shown in [18]. The designed antenna is placed on Quartz substrate and operates as a pair instead of a single element. This approach allows to use two end-fire antennas placed opposite each other in order to get a peak gain in the antenna broadside direction.

The above mentioned antennas were designed for higher frequencies (more than 2 GHz). However, in lower frequency bands there are a lot of potential candidates of wireless services which can serve as sources of harvesting energy.

The design of an antipodal Vivaldi antenna for RF harvesting has not been published in the open literature yet.

Our basic assumption for energy harvesting is that the antenna fixed on a wall harvests energy, with a high probability, only from a half-space. Our intention was to design the most efficient method of converting electromagnetic energy from different sources of service providers (GSM, WLAN, WiMAX, radar, etc.).

A conventional frequency-domain characterization of the developed antenna (frequency response of return loss, radiation patterns at selected frequencies) is completed by a time domain characterization and its comparison with selected reference antennas.

2. Antenna Design

In this paper, a planar antipodal Vivaldi antenna for RF energy harvester is presented. Next sections present the design of the antenna for energy harvesting, the simulated and measured results.

We have chosen the frequency band satisfying UWB requirements (approximately from 0.81 to 10 GHz) to cover bands of the main wireless communications technologies such as GSM 900, GSM 1800, GSM 1900, UMTS 2.1, WLAN 2.4 GHz, WLAN 5, radio spectrum bands L, S, C and more.

The configuration of the developed Vivaldi antipodal antenna for energy harvesting is shown in Fig. 2 together
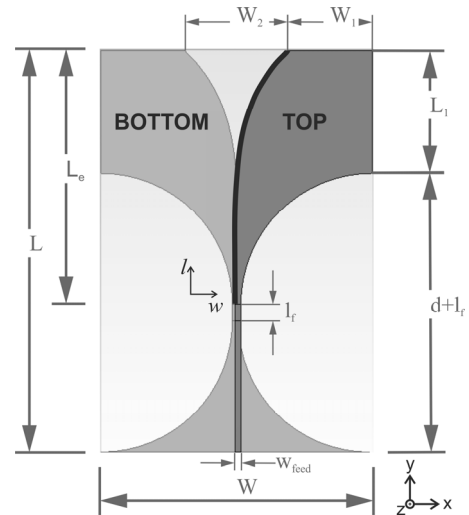

Fig. 2. Antipodal Vivaldi antenna with geometry parameters.

with the geometry parameters. The design objective is to obtain its compact size whilst maintaining the bandwidth requirement. The antenna consists of two coper layers; the top layer is connected to the signal conductor of the feeding line and the bottom layer is connected to the ground plane of the feeding line [11].

The designed UWB antipodal Vivaldi antenna for energy harvesting is printed on ARLON 600 substrate with relative permittivity $\varepsilon_r = 6.15$, loss tangent $\tan \delta = 0.003$ and height of the substrate is $h = 1.575$ mm [12].

The width of the antenna W is estimated by the lowest frequency of operation f_1 and by dielectric constant of the substrate ε_r. The start value W of the optimization process was stated by the equation [13]:

$$W = \frac{c}{f_1} \sqrt{\frac{2}{\varepsilon_r + 1}} \ . \tag{1}$$

Here, c is the speed of light in free space, f_1 is the lowest operating frequency and ε_r is permittivity.

The appearance of inner side of the antenna arms (darker curve in Fig. 2) is based on the principle of exponential curves. Curve equation has the form (CST Microwave Studio uses analytical expressions of the following equation) [13]:

$$l = \frac{L_2}{\sqrt[A]{W_3}} \cdot w^{\frac{1}{A}} \ . \tag{2}$$

Here, the variables A, L_2, and W_3 affect the shape of the exponential curve described in coordinates (w, l) according to Fig. 2.

The antenna arms are formed by connecting curves, such as lines (W_1, L_1 etc.) and quarter circles (both sides of the line l_f). Curves are designed in the same way by using the analytical curves. All statements curves of the antenna have their own variables. Variables were tuned and optimized in order to gain the required properties of the antenna.

The width of the microstrip feed line w_{feed} is calculated and matched to the characteristics impedance $Z_0 = 50\ \Omega$.

3. Simulated and Measured Results

The design and verification of the functionality of the antenna was performed in the full wave electromagnetic simulator CST Microwave Studio (CST MWS) [14].

Curvature of the exponential curve of the arm, the mutual distance between the arms W_2 and the length of the arms (length of the darker curve in Fig. 2 L_e) were parameters that had the strongest impact on return loss and radiation pattern.

CST MWS was used for tuning and optimization of the parameters of the antenna. Algorithm of Trust region framework was used for the optimization of the final value of the parameters. The antenna was analyzed by the time domain solver. Optimized dimensions and final shape of the designed antenna with port by CST MWS are shown in Tab. 1 and in Fig. 3. The port was included in the simulation model.

The simulation results are depicted in the charts for direct comparison between simulation and measurement. The frequency responses of the magnitude of return loss at the input of the simulated antenna and the measured antenna are depicted in Fig. 4. The far field radiation pattern and return loss of the considered antenna were measured by a network vector analyzer in a rectangular anechoic chamber operating in range from tens of MHz to 20 GHz.

The value of the simulated return loss is below 10 dB above 1.2201 GHz. For the measured antenna, the value of return loss is below 10 dB above 0.810 GHz with two small acceptable variations.
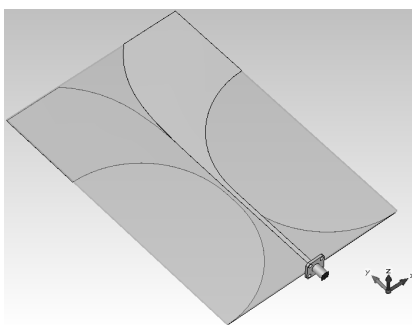

Fig. 3. Designed antenna with port in CST Studio.

W	128.01 mm	L_1	58.00 mm
W_1	39.55 mm	l_f	8.00 mm
W_2	48.94 mm	w_{feed}	2.75 mm
L	190.01 mm	d	124.00 mm
A	400 mm	L_2	120 mm
W_3	25.2 mm		

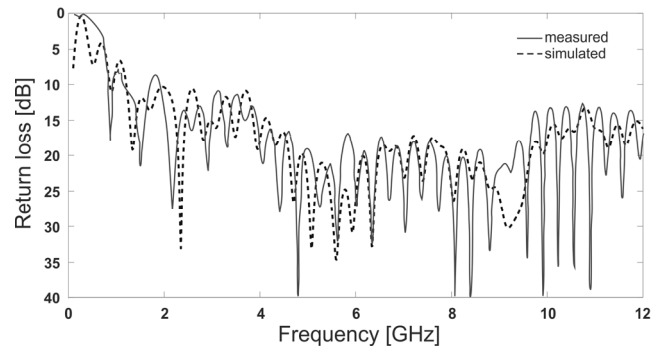**Tab. 1.** Optimized dimensions of the designed antenna.

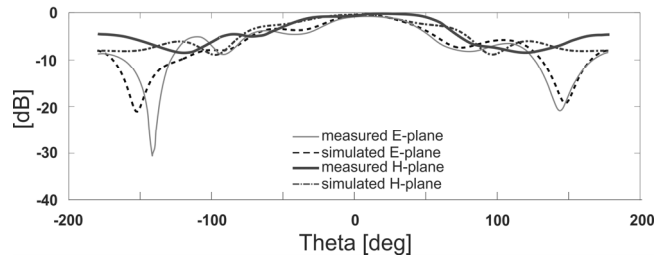**Fig. 4.** Return loss of measured and simulated antenna.

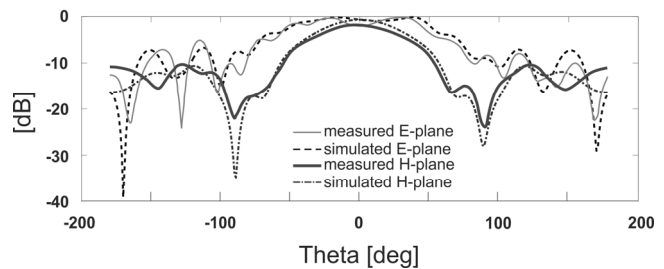**Fig. 5.** Simulated and measured radiation patterns at 2 GHz.

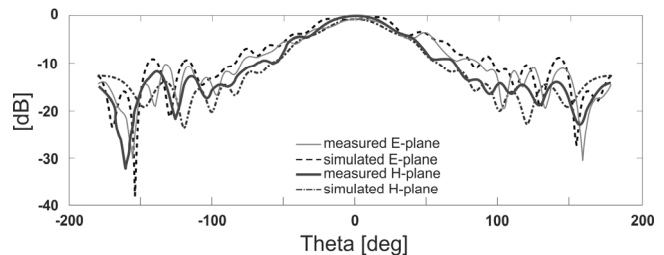**Fig. 6.** Simulated and measured radiation patterns at 4 GHz.

Fig. 7. Simulated and measured radiation patterns at 6 GHz.

The simulation and measurement results of radiation patterns for frequencies 2 GHz, 4 GHz and 6 GHz are shown in Fig. 5 - Fig. 7, where E-plane is X-Y plane and H-plane is Y-Z plane.

The designed Vivaldi antenna was measured in the time domain by a pulse UWB radar and compared with the commercial wideband antennas:

- Double ridged waveguide horn: RFspin DRH10 (0.74 to 10.5 GHz),

- Small bow-tie: GEOZONDAS AU – 1.0G4.5GR (1.0 to 4.5 GHz),

- Large bow-tie: GEOZONDAS AU – 0.8G2.4G-B (0.8 to 2.4 GHz).

The pulse UWB radar transmits a narrow pulse with the following parameters: Peak amplitude $U < 30V/50\Omega$ and width $t < 50$ ps. Reflected signals were acquired from the antenna after adjusting of observation window of the scope according to the lengths of *line a* and *b*. The shape and reference position of the excitation signal which is entering to the antenna were obtained by replacing the antenna with the calibration probe of type OPEN.

Principle diagram of measurement is shown in Fig. 8.

The pulse characteristics of the proposed Vivaldi antenna and commercial antennas are shown in Fig. 9 to Fig. 12. In these figures the exciting impulses are inserted. The exciting impulses are drawn to evaluate time relations of the measured signals, so the scale of the exciting impulse is reduced.
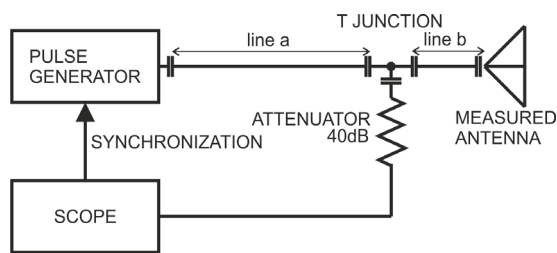

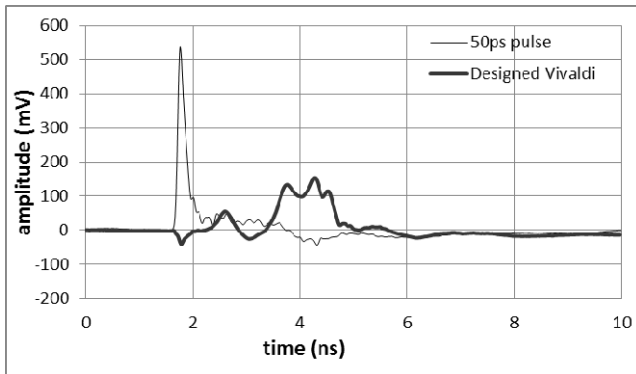**Fig. 8.** Block diagram of measurement with the pulse UWB radar.

Fig. 9. Reflected response of manufactured Vivaldi antenna on exciting pulse.
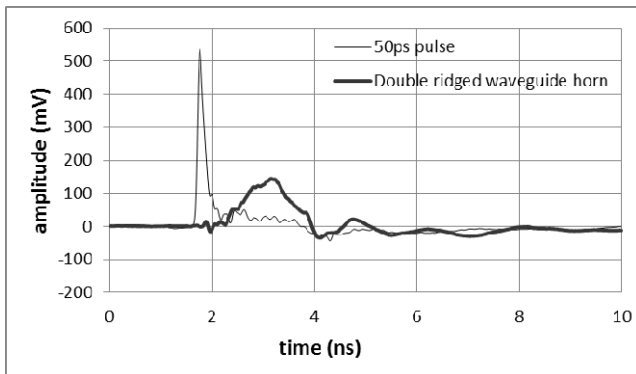

Fig. 10. Reflected response of double ridged waveguide horn antenna on exciting pulse.
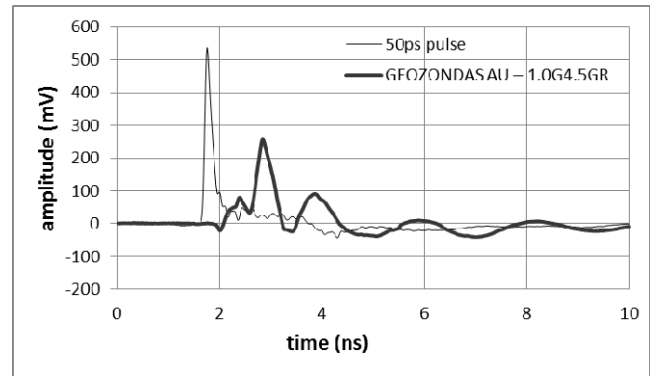

Fig. 11. Reflected response of GEOZONDAS AU –1.0G4.5GR on exciting pulse.
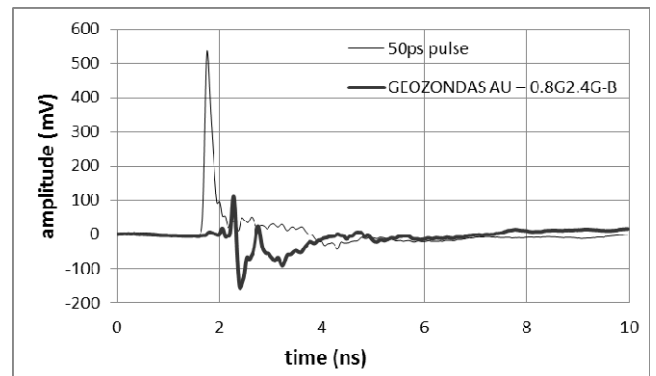

Fig. 12. Reflected response of GEOZONDAS AU–0.8G2.4G-B on exciting pulse.

4. Conclusion

The suitable antipodal Vivaldi antenna for RF energy harvesting was presented in this paper. The antenna was designed in the software CST Microwave Studio and the final dimensions of the antenna were obtained using optimization methods that are offered in this program. The manufactured antenna is depicted in Fig. 13.

The antenna operates in the frequency band from 0.8 GHz to 12 GHz with average gain 6.32 dBi and fractional bandwidth $BW = 163\%$. Return loss of the antenna
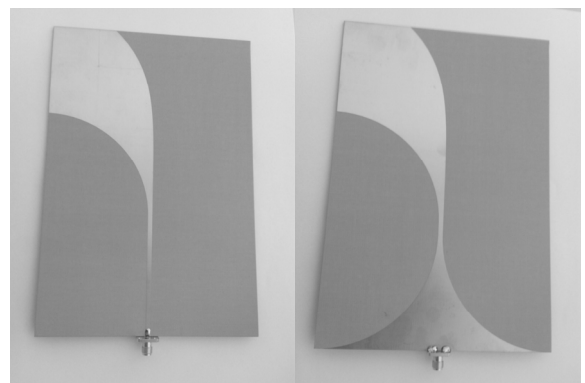

Fig. 13. Manufactured antenna.

between 0.8 to 2 GHz varies around the value 10 dB (Fig. 4). This small variation is acceptable for energy harvesting and UWB requirements. The antenna covers the frequency bands of multiple wireless communication systems. The measurement results confirmed simulated results.

The reflected impulse responses (Fig. 9 to Fig. 12) of the designed Vivaldi antenna have satisfactory frequency character in the wide bandwidth applications. Positive feedback from measurements in the time domain is the antenna has a very low ringing in comparison with commercially available antennas. The results presented above predestinates this antenna not only for the RF energy harvesting but also for applications sensitive to changes in group delay receiving and transmitting signal e.g. for UWB radars.

Wide bandwidth of the designed antenna and its relatively small size with low cost fabrication provide appropriate properties for the use in energy harvesting. The antenna might be used as an element of the antenna array to obtain a high gain and preserve a very high frequency bandwidth. The designed antenna can be used for RF energy harvesting and obtained RF energy can be reused to operate low-power electronic devices.

Acknowledgments

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Zbyněk RAIDA was born in 1967 in Opava. He received his Ing. degree and Dr. degree from Brno University of Technology (BUT) in 1991 and 1994, respectively. In 1996-1997, he was with the Laboratoire de Hyperfrequences, Universite Catholique de Louvain, Belgium, working on variational methods of numerical analysis of electromagnetic structures. In 2006-2013, he was the head of the Dept. of Radio Electronics, and in 2010-2015 the head of the SIX Center. At present, he is a professor at the Dept. of Radio Electronics, Faculty of Electrical Engineering and Communication, BUT. His research interests cover numerical modeling and optimization of electromagnetic structures, exploitation of artificial neural networks for solving electromagnetic compatibility issues, and the design of special antennas. Zbyněk Raida is a member of IEEE Microwave Theory and Techniques Society.