

UWB Vivaldi Antenna for Impulse Radio Beamforming

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Abstract—In this paper, two different types of Vivaldi antenna are designed and tested suitable for electromagnetic beamforming. The first is an antipodal Vivaldi antenna, while the other is a tapered slot Vivaldi antenna. They are both ultra wideband antennas for the 1GHz to 5GHz frequency band. They have low impulse distortion and the voltage standing wave ratio (VSWR) less than 2 throughout the entire bandwidth. The antennas are used for impulse radio beamforming.

I. INTRODUCTION

Ultra-wideband (UWB) transmission has recently received significant attention in both academia and industry for applications in wireless communications [1][2]. UWB has many benefits, including high data rate, availability of low-cost transceiver, low transmit power and low interference. The Vivaldi antenna is one of the classical ultra wideband antennas which was first investigated by P.Gibson in 1979, and many improvements to the initial design have since been presented [3][4]. A Vivaldi antenna is basically a planar traveling wave antenna with end-fire radiation. After being invented, the Vivaldi antenna is the preferred candidate for UWB applications due to its wide bandwidth, low cross polarization and highly directive patterns [5].

When a number of close-by antennas are transmitting simultaneously, the electromagnetic (EM) waves are interacting and may both cancel and/or reinforce each other. The pattern of EM field is known as lobes or beams. By proper control of the interacting transmitters, the beams may be shaped or formed, a process known as *beamforming*. Although most beamforming are implemented as phase adjustment of carrier-based EM waves, we will work with impulse based beamforming getting rid of grating lobes.

There are many advantages of using directional antennas both in UWB impulse radar and communications. First of all, the energy efficiency is good. While a standard omnidirectional antenna transmits the energy in all directions, a directional antenna is capable of directing most emitted power in a lobe or beam. In this way a receiving antenna can get more of the radiated energy, thus reducing the required transmission power.

High-resolution beamforming has several interesting applications within the radar field. For example, light-weight electromagnetic cameras could be developed to replace the heavy imaging systems currently in use at hospitals.

The Vivaldi antenna is an ideal type of antenna used for EM beamforming, The high directivity is important for focusing most of the radiated energy in well-controlled beams. To transmit short-duration Gaussian pulses, the wide bandwidth of the antenna is crucial for reducing distortion.

II. VIVALDI ANTENNA

Theoretically, Vivaldi antennas have an unlimited range of operating frequencies with constant beamwidth over the entire bandwidth. A major advantage of this antenna type is that the ultra wide bandwidth can be achieved using antipodal tapered profiles and exponential tapered profiles with its inherently simple wideband transition from microstrip line to parallel-strips [6].

A. Antipodal Vivaldi Antenna

The structure and designed parameters of the antipodal Vivaldi antenna are depicted in Fig. 1. A smooth transition between twin line and microstrip line is used to remove the bandwidth limitation of transition in the conventional Vivaldi antenna. The microstrip line and ground plane are on different sides of the substrate and gradually flare out in opposite directions to form the tapered slot [7]. The assigned dimensions are developed for the specified frequency band.

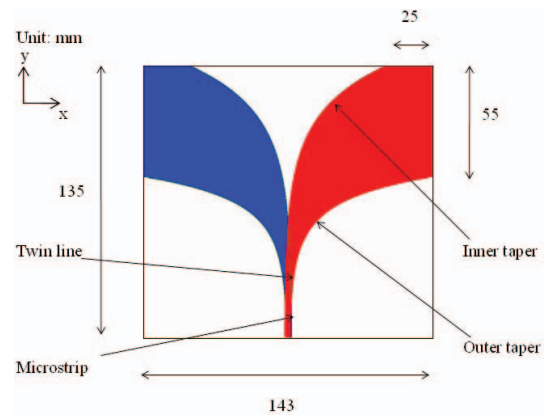


Fig. 1. Structure and designed parameters of antipodal Vivaldi antenna.

As the antipodal Vivaldi antenna operate as a resonant antenna at the lower end of frequency band, the antenna width W is determined based on the lowest frequency f_{\min} and effective dielectric constant ϵ_{eff} in the following equation [7]:

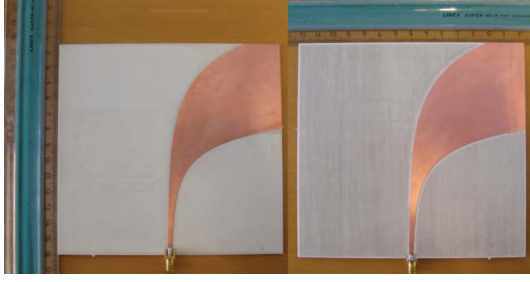


Fig. 2. Top view and bottom view of antipodal Vivaldi antenna.

$$W = \frac{c}{2 \times f_{\min} \times \sqrt{\epsilon_{\text{eff}}}}$$

Thus, an increased antenna width affects the lower end in its frequency band. Fig. 2 displays the top view and bottom view of the designed antipodal Vivaldi antenna. In this design, a symmetrical pair of conductor serves as impedance transformer, leading to gradual change of impedance from 50Ω in the feed of the antenna to free space in the end.

B. Tapered slot antenna

The geometry of a tapered slot Vivaldi antenna is shown in Fig. 3. Its tapered profile is described by an exponential function. The tapered slot Vivaldi antenna is excited via the microstrip-to-slotline transition. The transition construction exploits wideband features of a microstrip radial stub used as a virtual wideband short. The microstrip is virtually shunted to the second half of the slotline metallization while the first half serves as a ground metallization for the microstrip line. It is necessary to transform the impedance of the input feeding microstrip line to the input impedance of the transition. Therefore, the linear microstrip taper is used as the input impedance transformer [8][9].

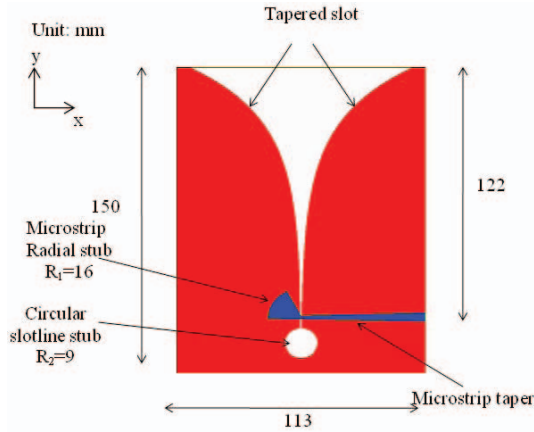


Fig. 3. Structure and designed parameters of tapered slot Vivaldi antenna.

Like the antipodal Vivaldi antenna, when designing the tapered slot Vivaldi antenna there is also a trade-off between the antenna size and its bandwidth towards low frequency. The top and the bottom view of the tapered slot Vivaldi antenna is shown in Fig. 4.

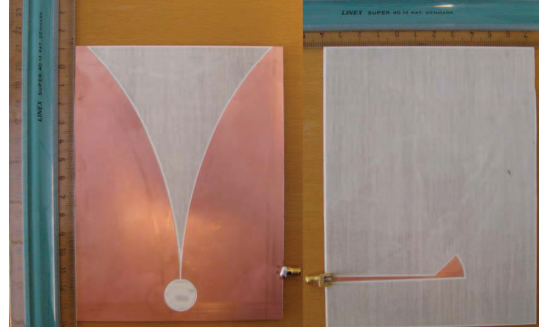


Fig. 4. Top view and bottom view of tapered slot Vivaldi antenna.

C. Beamforming

Electromagnetic beamforming is often achieved by using a phased array transmitting a signal with carrier wave. A phased array is an array of antennas where each of the antennas transmits a phase shifted version of the signal. Usually this is accomplished by using phase-shifters. For pulse-based signals, the phase shifters are often replaced by time delays. By controlling the firing-sequence when each of the antennas is transmitting, we can control the direction of the major part of the transmitted energy. This way of achieving beamforming is referred to as time-domain beamforming. A more common term for time domain beamforming when controlling the firing-sequence of impulses is timed array [10].

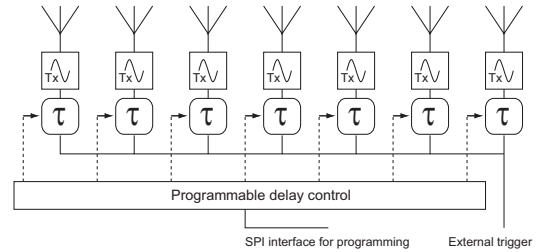


Fig. 5. Beamforming setup.

As shown in Fig. 5 the idea of impulse radio beamforming is simple. A number of identical Gaussian transmitters are individually controllable with a trigger pulse. In order to generate a suitable sequence of transmitted pulses, a delay element is inserted between a global trigger pulse and each of the transmitters. By adjusting the relative phase differences of signals transmitted by several antennas, constructive and destructive interference will set up a radiation pattern, a process known as beamforming. The expected radiation pattern depends on the array geometry, the antenna weights and also the number of antennas. The beamwidth depends on the antenna spacing. The larger antenna spacing, the smaller beamwidth and the better resolution. The number of antennas determines the number of sidelobes and the peak of the main lobe.

III. EXPERIMENTAL RESULTS

Two different types of Vivaldi antenna are fabricated on Rogers RO4350B substrate with a relative constant of 3.48, thickness of 1.52mm and loss tangent of 0.0031. These antennas are designed for 1^{st} derivative Gaussian pulse transmission. The pulses fill a bandwidth from 1GHz to 5GHz. All parameters of the Vivaldi antennas are optimized by Ansoft High Frequency Structure Simulator (HFSS) and then fabricated to perform s-parameter measurements for validation. The measurement results are obtained using ZVB 20 Vector Network Analyzer. Both antipodal and tapered slot Vivaldi antenna match the feeding port to 50Ω . They all have small dimensions and good performance.

A. Antipodal Vivaldi Antenna

As depicted in Fig. 6 and Fig. 7, the antipodal Vivaldi antenna presents good return loss better than -10dB over the wide bandwidth from 1GHz to 5GHz. In most of frequency band, VSWR less than 1.5 indicating that the reflection coefficient is less than 0.2 across the quoted frequency range. Hence, of the power delivered to the antenna, only 4% of the power is reflected back to the transmitter. Moreover, the ground plane around the feeding port is removed in this antenna. The removal of the ground plane is derived from the investigation in [7]. This leads to an increase of the impedance bandwidth without changing the radiation pattern. Consequently, measurement results of S-parameters (S_{11} , S_{12}) and VSWR show that this antipodal Vivaldi antenna has a very wide bandwidth and it can be used for applications using frequency bands up to 20GHz. Fig. 8 is the phase behavior of the antenna. It can be seen that the antenna has a good linear phase response.

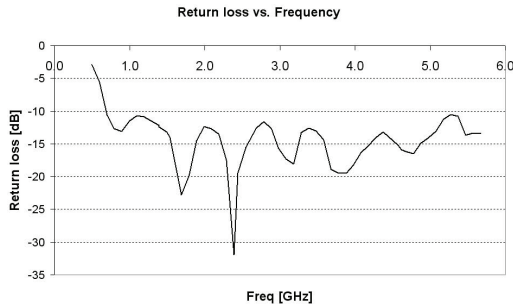


Fig. 6. Measured return loss of antipodal Vivaldi antenna.

The antenna gain vs. frequency is given in table I and plotted in Fig. 9. The gain is measured at the distance of 1m. Overall, this antenna has high gain values as in most part of the frequency band, the gain is higher than 6dBi. For comparison, the small antipodal Vivaldi antenna in [8] has the gain less than 6dBi.

The simulated radiation pattern of the antenna is shown in Fig. 10. The designed antipodal Vivaldi antenna has a small backward radiation in both E-plane/Azimuth plane and H-plane/Elevation plane. As a result, its directivity is remarkably

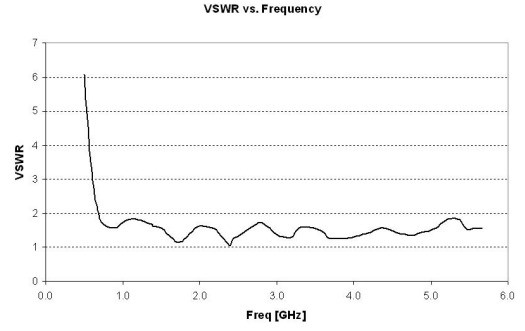


Fig. 7. Measured VSWR of antipodal Vivaldi antenna.

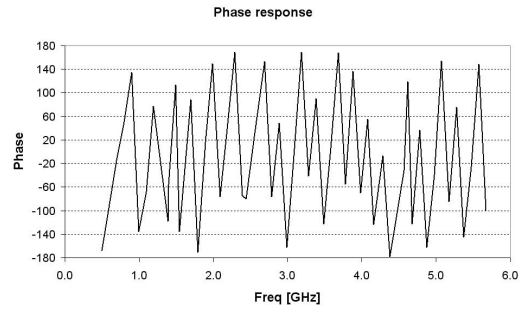


Fig. 8. Measured phase response of antipodal Vivaldi antenna.

TABLE I
MEASURED GAIN VALUES OF ANTIPODAL VIVALDI ANTENNA.

| Freq (GHz) | Gain (dBi) | Freq (GHz) | Gain (dBi) |
|------------|------------|------------|------------|
| 1.00 | 4.10 | 3.20 | 10.20 |
| 1.20 | 3.20 | 3.40 | 9.80 |
| 1.40 | 3.10 | 3.60 | 8.00 |
| 1.60 | 3.60 | 3.80 | 6.50 |
| 1.80 | 5.80 | 4.00 | 6.40 |
| 2.00 | 7.70 | 4.20 | 7.30 |
| 2.20 | 8.20 | 4.40 | 6.70 |
| 2.40 | 10.60 | 4.60 | 6.50 |
| 2.60 | 9.20 | 4.80 | 5.00 |
| 2.80 | 9.20 | 5.00 | 5.50 |
| 3.00 | 9.20 | | |

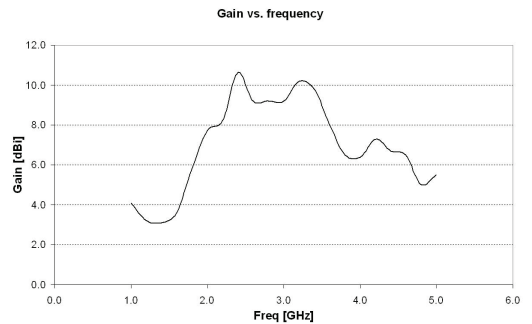


Fig. 9. Measured gain vs. frequency of antipodal Vivaldi antenna.

improved in comparison with the antipodal Vivaldi antenna in [7] and in [8].

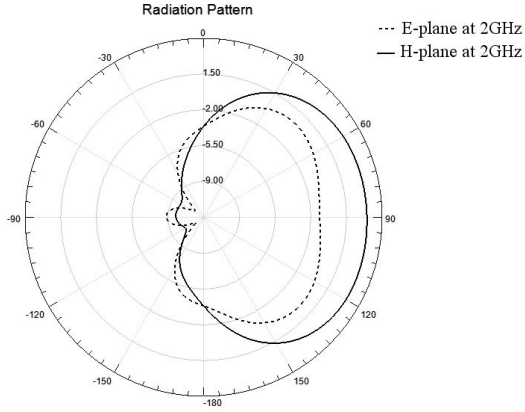


Fig. 10. Simulated radiation pattern of antipodal Vivaldi antenna.

B. Tapered Slot Vivaldi Antenna

Measured results in Fig. 11 and Fig. 12 show that this tapered slot Vivaldi antenna presents good return loss better than -10dB between 1GHz and 5GHz. This corresponds to VSWR less than 2 for operation throughout the aimed frequency band. This antenna also has a good linear phase response as displayed in Fig. 13. The designed antenna has small dimension $113\text{mm} \times 150\text{mm}$ while the antenna in [11] has $203\text{mm} \times 292\text{mm}$. Measurement results also show that this antenna has a very small distortion on the transmitted 1st derivative Gaussian pulse.

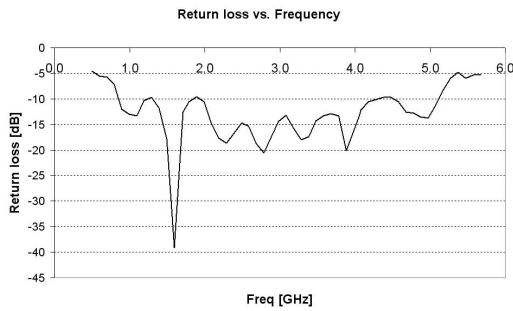


Fig. 11. Measured return loss of tapered slot Vivaldi antenna.

The measured gain values at the distance of 1m between two identical antennas are given in table II and are plotted in Fig. 14. It can be seen that the gain values are higher than 8dBi in most part of the designed frequency band in comparison with the antenna in [12] achieving a maximal gain values of 8dBi.

Fig. 15 displays the simulated radiation pattern of tapered slot Vivaldi antenna achieving by Ansoft HFSS. Although its backward radiation is stronger compared to the antipodal Vivaldi antenna it is still suitable for beamforming.

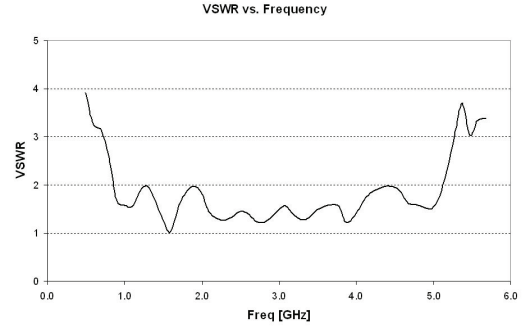


Fig. 12. Measured VSWR of tapered slot Vivaldi antenna.

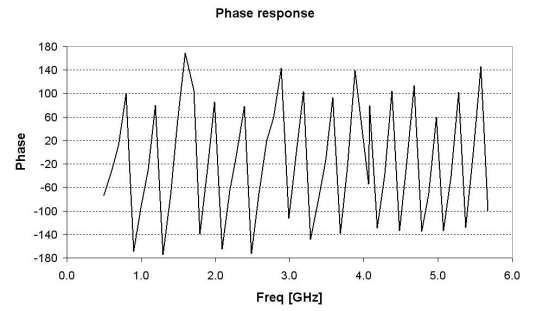


Fig. 13. Measured phase response of tapered slot Vivaldi antenna.

TABLE II
MEASURED GAIN VALUES OF TAPERED SLOT VIVALDI ANTENNA.

| Freq (GHz) | Gain (dBi) | Freq (GHz) | Gain (dBi) |
|------------|------------|------------|------------|
| 1.00 | 3.80 | 3.20 | 10.20 |
| 1.20 | 3.10 | 3.40 | 10.10 |
| 1.40 | 3.30 | 3.60 | 8.40 |
| 1.60 | 10.70 | 3.80 | 7.50 |
| 1.80 | 8.80 | 4.00 | 7.60 |
| 2.00 | 8.40 | 4.20 | 8.10 |
| 2.20 | 9.80 | 4.40 | 8.20 |
| 2.40 | 5.60 | 4.60 | 7.90 |
| 2.60 | 9.00 | 4.80 | 5.90 |
| 2.80 | 9.50 | 5.00 | 4.90 |
| 3.00 | 10.10 | | |

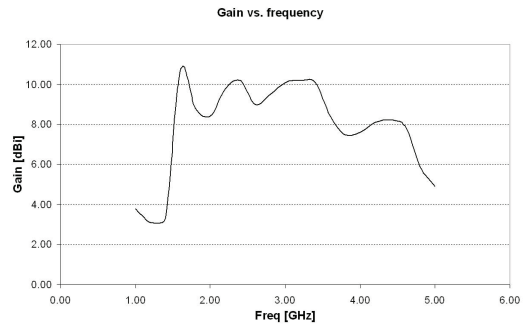


Fig. 14. Measured gain vs. frequency of tapered slot Vivaldi antenna.

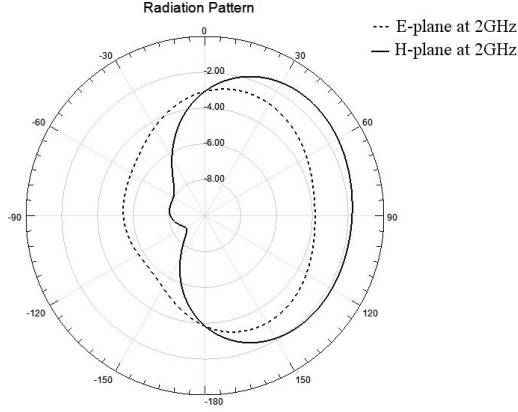


Fig. 15. Simulated radiation pattern of tapered slot Vivaldi antenna.

C. Beamforming

In this section, the measurement results of beamforming will be given. There are different ways of arranging the antennas in an antenna array depending on the desired outcome. For evaluation purposes a linear one dimensional arrangement of the antennas is used. All seven antennas is transmitting and tuned by delay programming to be focused as depicted in Fig. 16.

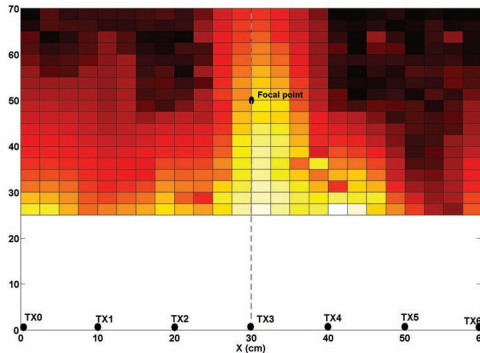


Fig. 16. Measured EM field of beamformer.

The beamformer is programmed to focus at the point (30cm, 50cm). Each antenna transmits 1st derivative Gaussian pulses, whose bandwidth is [1GHz – 5GHz], at different time decided by the programmable delay element. Fig. 16, show the measured EM field of the array with antenna spacing of 10cm which is approximately one wavelength. In these figures the EM fields in light areas are stronger than the dark areas. The X axis indicates the transmitter line-up and the Y axis gives the depth. The EM field is measured from 25cm to 70cm in the Y direction. It can be seen that the beamformer has good performance while energy is focused on focal point.

IV. CONCLUSION

Two types of Vivaldi antenna are designed on Rogers RO4350B substrate for electromagnetic beamforming. They are both tuned for the [1GHz – 5GHz] frequency band

and show significant gain. The proposed antennas show low impulse distortion and the VSWR is less than 2 over the entire bandwidth. Simulated and measured results indicate that antipodal Vivaldi antenna has to be larger than tapered Vivaldi antenna in order to achieve a similar return loss. However, a very wide bandwidth can easily achieve by the removal of the ground plane around the feeding port. Furthermore, antenna gain value will be higher with a larger antenna for both types of Vivaldi antenna. There are some trade-offs between the bandwidth and the gain as well as the size and the low end in frequency band of the Vivaldi antennas. Due to the lack of good facilities and measurement conditions, only simulated radiation patterns of Vivaldi antennas are given. Using Vivaldi antennas for beamforming is also introduced. The wide bandwidth of Vivaldi antennas is crucial for reducing distortion. Besides, the high gain and high directivity lead to a decrease in energy consumption as the radiated energy is directed towards targets instead of transmitting in all directions.

ACKNOWLEDGMENT

The research has been sponsored by Norwegian Research Council project number 187857/S10 and was carried out at the Nanoelectronics research group, Department of Informatics, University of Oslo, Norway.

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