Design and Analysis of Vivaldi Antenna for Measuring Electromagnetic Compatibility

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Abstract - The paper presents design and characterization of a pair of Vivaldi antennas in the frequency range from 0.5 to 4 GHz. The design procedure is described in detail together with analysis of the antenna current density distribution and the operating mechanism. Simulated and measured relevant results are compared and discussed. The antennas are intended to be used for electromagnetic field measurements over wide frequency range (by which several narrow-band antennas can be replaced). It is shown that antenna exhibits stable characteristics and is relatively low-cost, so it can be considered as a suitable solution for high frequency component of the electromagnetic compatibility (EMC) measurement system currently being developed within Department of Electrical Engineering Fundamentals and Measurements at University of Zagreb, FER.

Keywords - Ultrawideband antenna; Vivaldi antenna; antenna factor; Electromagnetic compatibility measurements

I. INTRODUCTION

The wearable electronic and computing devices have been largely developed within last decade with promising applications in health monitoring, general safety together with general entertainment and augmented reality. Such development has naturally led to merging the traditional two-dimensional horn antenna [6–8] with its applications can be extended readily when needed. Furthermore, its design allows for further modifications and optimizations, as well as convenient integration in arrays [6, 7]. Here we present the design of Vivaldi antenna version with simple coaxial feeding together with characterizing its operation in terms of gain and antenna factor in the frequency range from 0.5 GHz and 4 GHz, since this is at the moment the supposed range of its application in textile material characterization. We also show that the developed antenna has however even larger bandwidth so its applications can be extended readily when needed.

II. THE VIVALDI ANTENNA DESIGN

Using the commercial software CST Microwave Studio [9] we have optimized the Vivaldi antenna (Fig. 1) for operation between around 0.5 GHz and 4 GHz, as shown in Fig. 1. Each arm of the antenna (i.e. the exponential taper) is given by the equation:

\[ y = A \cdot e^{pn} \]  

(1)

where \( A \) is the opening half-width at the antenna narrow end and \( p \) is the taper rate. The initial parameters \( A \) and \( p \) are chosen according to the prescription in [8], which basically requires that the total length and width of the antenna are comparable to the wavelength at lowest operating frequency.

We have chosen to excite the antenna directly via coaxial cable which has considerably simplified the design of the antenna feeding and in final design has enabled some reduction in total antenna dimensions compared to the ones arising from [8]. The used antenna substrate is FR408HR [10]. Although the lowest frequency of operation has been initially chosen as 1 GHz, we have managed to optimize the lowest operating frequency to...
500 MHz with reasonable total dimensions. The relevant parameters of the antenna geometry after optimization are summarized in Table I.

![Antenna sketch](image)

**Figure 1.** The sketch of the proposed Vivaldi antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-opening A</td>
<td>0.1</td>
</tr>
<tr>
<td>Taper rate p</td>
<td>0.0482</td>
</tr>
<tr>
<td>Antenna dimensions</td>
<td>14 cm x 17 cm</td>
</tr>
<tr>
<td>Feeding position</td>
<td>4 mm from the narrow opening</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Substrate permittivity</td>
<td>3.69</td>
</tr>
</tbody>
</table>

The antenna radiation mechanism is illustrated in Fig. 2, where the snapshots of electric field tangential component in the antenna plane are shown for several frequencies. It can be seen that the tapered slot acts as a transmission line with smooth impedance transition towards free space, which makes the radiation mechanism similar to the one in the horn antenna [8] (hence Vivaldi antenna can be considered as 2D horn antenna). The calculated radiation patterns (Fig. 3) exhibit maximum at the direction of the antenna opening at all the considered frequencies, while the maximum gain (Table II) and radiation pattern shape are relatively stable at higher considered frequencies. Although there is some discrepancy in radiation pattern shape at frequencies of 1 GHz and 2.45 GHz, this possesses no major relevance for the envisaged application in electromagnetic compatibility measurements, as the maximum direction is stable at all frequencies.

**A. The manufactured prototype**

Based on the described simulation results two prototypes of the Vivaldi antennas are manufactured. Both prototypes (Fig. 4) are excited with 0.5 m section of the 50 Ω commercial coaxial RG174 cables [11], for which the measured loss characteristics up to 10 GHz (using R&S ZVA 40 network analyzer) is given in Fig. 5. It can be seen that the cable introduces losses of less than 2 dB for frequencies up to around 6 GHz and up to 3.25 dB for frequencies up to 10 GHz. At this stage the losses can be considered low enough for the antenna application, while the use of relatively long cable enables practical integration of the antennas into the measurement system and keeps the low overall cost of the structure. Since the antenna is to be used as a measurement antenna, the introduced losses are not expected to degrade measurement system performance and are compensated with relatively high gain of the antenna itself (of course, at any stage in the future the cable can be easily replaced or shortened if needed).

![Antenna radiation pattern snapshots](image)

**Figure 2.** Snapshots of tangential (x- and y-) components of the electric field at the antenna plane: a) f=1 GHz; b) f=2.45 GHz; c) f=5.8 GHz; d) f=8.5 GHz

![Antenna radiation pattern 3D plots](image)

**Figure 3.** Qualitative 3D plots of the calculated antenna radiation patterns at: a) f=1 GHz; b) f=2.45 GHz; c) f=5.8 GHz; d) f=8.5 GHz

**TABLE II. THE CALCULATED ANTENNA GAINS AT REPRESENTATIVE FREQUENCIES**

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Calculated gain [dBi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.15</td>
</tr>
<tr>
<td>2.45</td>
<td>8.36</td>
</tr>
<tr>
<td>5.8</td>
<td>7.42</td>
</tr>
<tr>
<td>8.5</td>
<td>6.55</td>
</tr>
</tbody>
</table>
The antenna measurements have been performed using R&S ZVA 40 and Keysight FieldFox N9913A network analyzers. The first analyzer was used for measurements up to 10 GHz, to analyze the antenna and cable behavior at frequencies somewhat beyond upper operating range (and find possible improvements for future), while the second analyzer is used for measurements from 500 MHz to 4 GHz since this is the range the measurement system with Vivaldi antenna is supposed to operate. The frequency characteristics of measured and calculated magnitudes of the input reflection coefficients are compared in Figs 6 and 7 both for range up to 10 GHz and (more detailed) up to 4 GHz, respectively. In addition, in Fig. 7 the measurements on the second prototype are also shown, and here it can be seen that the second prototype exhibits similar frequency behavior as the first one. From these results it can also be seen that very good correspondence between measured and simulated results has been obtained (note that some minor discrepancies arise mostly due to cable losses), while the manufacturing procedure is generally robust and reproducible.

\[ G_{TOT,\,db} = \frac{1}{2} \left( |S_{21}|_{\,db} - 20 \log \left( \frac{\lambda}{4 \pi d} \right) - M_{\,db} \right), \]  
\( (2) \)

where \( |S_{21}| \) is the measured magnitude of transmission coefficient, \( |S_{11}| \) is the measured magnitude of antenna input reflection coefficient (linear), \( \lambda \) is the wavelength and \( d \) is the distance between antennas. The mismatch factor \( M \) in [dB] is given as:

\[ M_{\,db} = 10 \cdot \log \left( 1 - |S_{11,\,T}|^2 \right) + 10 \cdot \log \left( 1 - |S_{11,\,R}|^2 \right), \]  
\( (3) \)

where \( |S_{11,\,T}| \) and \( |S_{11,\,R}| \) are measured (linear) magnitudes of reflection coefficient of the transmitting and receiving antennas, respectively (Fig. 7). Note that in (2) we assume that the gains of the antennas are the same, which is the fair and standard assumption in antenna measurements with two basically the same antennas [8].

By subtracting the cable losses from Fig. 5 one obtains the gain of the structure itself. It roughly corresponds to the gain predicted by simulation (Table II). The realized antenna gain is thus in line with similar Vivaldi antenna realizations [6-8], and in line with the expectations (as mentioned before, total gain can be somewhat improved by replacing the cable with one having lower losses if needed).

\[ \frac{\lambda}{4 \pi d} \]  
\[ \frac{\lambda}{4 \pi d} \]

**B. The antenna gain**

In the next measurement campaign two Vivaldi antennas have been put at the distance of 2 meters and oriented to the same polarization. The magnitude of transmission coefficient has been measured in order to find the total gain (antenna plus cable) and eventually the antenna factor. The results are shown in Figs 8 and 9. The measured total gain in [dBi] is calculated from the transmission coefficient as:

\[ G_{TOT,\,db} = \frac{1}{2} \left( |S_{21}|_{\,db} - 20 \log \left( \frac{\lambda}{4 \pi d} \right) - M_{\,db} \right), \]  
\( (2) \)

where \( |S_{21}| \) is the measured magnitude of transmission coefficient, \( |S_{11}| \) is the measured magnitude of antenna input reflection coefficient (linear), \( \lambda \) is the wavelength and \( d \) is the distance between antennas. The mismatch factor \( M \) in [dB] is given as:

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The calculated antenna factor for the proposed Vivaldi antenna is given in Fig. 10, while the values of the antenna factor at representative frequencies are given numerically in Table III. The values of the antenna factor in [dB/m] are eventually obtained as:

$$AF_{[\text{dB/m}]} = 20 \cdot \log \left( \frac{1}{m} \right) = 20 \cdot \log \left( \frac{9.73}{\lambda \cdot \sqrt{G}} \right).$$

III. CONCLUSION

In this paper we have proposed a simple Vivaldi antenna for electromagnetic compatibility measurements and characterization of conductive textile materials. The antenna is shown to operate between 500 MHz and around 6 GHz, while more detailed characterization is performed for frequencies up to 4 GHz since this is the envisaged operating range of the measurement system to be developed. The good correspondence of simulated and measured results is obtained, while the antenna is shown to possess high gain, reasonably small dimensions and is cost-effective for implementation in measurement system since it is capable of replacing several narrow-band antennas. The obtained antenna factor is in line with commercial antenna realizations for electromagnetic compatibility (EMC) measurements.

The future work will comprise the integration of the antenna into an EMC measurement system and development of method for measuring shielding efficiency and conductivity of conductive textile materials. In addition, the proposed design will be adapted for textile
version of Vivaldi antenna for use in body-centric ultrawideband systems. The methods for integration of textile Vivaldi antennas into an array will also be considered.

REFERENCES


