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REGULAR ARTICLE

Design of a Compact Vivaldi Antenna for Wearable Tactical Applications

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The increased demand for wearable communication systems in tactical and military applications involves the creation of small, lightweight, high-performance antennas. This study describes the design and implementation of a small Vivaldi antenna tailored for wearable tactical application bands. To accomplish compactness and flexibility, the antenna is built with a flexible substrate material that supports to the human body while being highly efficient. Performance factors like as gain, bandwidth, radiation pattern are assessed to ensure that the antenna fits the severe criteria of wearable devices. The tiny design minimizes size without sacrificing performance, making it appropriate for integration into tactical wearable systems. Simulation and experimental results demonstrate that the antenna provides stable radiation characteristics and good efficiency. The Vivaldi antenna for wearable military applications was designed and a parametric study was conducted. The impact of return loss, VSWR, gain, and radiation pattern on the design of a single element antenna are explored. The results of simulations performed with Ansoft ADS, a high frequency electromagnetic field simulation program, are presented and reviewed.

Keywords: Wireless communication (WC), Wearable communication, Vivaldi antenna, VSWR, Tactical Antenna.

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1. INTRODUCTION

Vivaldi antennas are a type of planar, broadband, end-fire antennas known for their ultra-wideband (UWB) performance, high directivity, and ease of integration with planar circuits [1]. Their tapered slot structure allows for wideband frequency operation, making them suitable for various communication and sensing applications [2]. Wearable antennas must conform to the human body, be lightweight, flexible, and maintain performance despite movement and environmental factors. Materials like textiles, flexible substrates, and conformal designs are commonly employed [3, 4].

Low-profile antennas are essential for minimizing the bulkiness of wearable devices [5]. Techniques to achieve low profiles include the use of compact geometries, folded structures, and integration with substrates that allow for reduced thickness without compromising performance [6]. While Vivaldi antennas are traditionally used in fixed installations, recent research explores their adaptation for wearable scenarios, focusing on flexibility, integration with textiles, and maintaining broadband performance in dynamic environments [7, 8].

Lewis et al. [9] introduced tapered slot antenna as a broadband stripline Single Element Antenna element capable of multioctave bandwidths in his study. Following TSA, Vivaldi antenna, an exponentially tapered slot antenna, originated by Gibson [10]. Gibson stated that Vivaldi antenna had significant gain and linear polarization in a frequency range from below 2 GHz to above 40 GHz. Gibson's Vivaldi antenna with an asymmetric one-sided microstrip to slotline transition was constructed on alumina using microwave photolithographic thin film techniques. It served well as an 8-40 GHz video receiver module.

Yngvesson et al. [11] compared three different TSAs, linearly tapered slot antenna (LTSA), constant width slot antenna (CWSA) and Gibson's exponentially tapered slot antenna, Vivaldi antenna. He found that Vivaldi antenna had the smallest side lobe levels followed by CWSA and LTSA whereas it had the widest beamwidth and CWSA had the narrowest one [12-13]. He also investigated the effect of dielectric substrate thickness and the length of Vivaldi antenna on the beamwidth [14-15].

2. DESCRIPTION OF VIVALDI ANTENNA

The Vivaldi antenna, having an exponentially tapered slot profile, is a type of tapered slot antenna

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(TSA). The distinctive feature of TSA is a slotline widening with distance from the feed forming the radiating section of the antenna. The profile of radiating section or taper specifies the different types of TSA. The best-known types of TSA which are linearly tapered slot antenna (LTSA), constant width slot antenna (CWSA) and exponentially tapered slot antenna (Vivaldi) are shown in Figure 1 below. TSAs are efficient and geometrically simple with significant gain and wide bandwidth and appreciably light weight as mentioned before. Moreover, this kind of antenna produces symmetrical radiation patterns with high directivity and low side lobe levels.

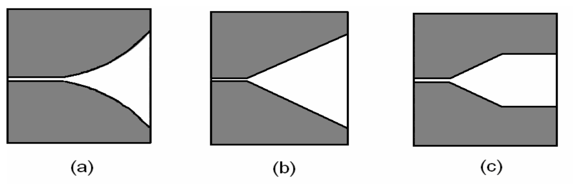


Fig. 1 – Types of TSA; (a) exponentially tapered (Vivaldi), (b) linearly tapered (LTSA) and (c) constant width slot antenna (CWSA)

The Vivaldi antenna, as a member of class of TSA, is most effective with a slotline feeding. Thus, a transition shall be designed to couple signals to the slotline of Vivaldi from the transmitter or receiver circuitry. The transition shall be low loss over a wide frequency range so as not to limit operating bandwidth. It shall also be compact and easy to fabricate. The feeding techniques may be divided into two types mainly as directly coupled transitions and electromagnetically coupled transitions [16-17].

3. PROPOSED DESIGN

This chapter describes the parametric study of Vivaldi antennas regarding the design of an antenna with the given specifications. The effect of each parameter is investigated performing simulations with Ansoft ADS®. The Vivaldi antenna model is given in Figure 2. The following specifications are used as the case study to apply the design methodology discussed in this chapter: 8.5-10.5 GHz frequency bandwidth, return loss better than 10 dB and 50 Ω characteristic impedance in the feeding section.

Electromagnetically coupled transitions are more advantageous compared with direct coupling due to ease of implementation as discussed in Chapter 2. Microstrip to slotline and antipodal slotline transitions are unbalanced electromagnetically coupled feeding techniques. These kinds of transitions are unable to produce a spatially symmetric structure leading to perfectly linear polarization in the principal planes unlike the balanced transitions. Besides, microstrip to slotline transition limits the wide bandwidth of Vivaldi antenna whereas antipodal slotline transition produces unacceptable cross polarization levels as stated earlier. Stripline to slotline and balanced antipodal transitions show symmetry owing to their balanced structures. Balanced antipodal slotline can operate in a multi-octave bandwidth with good cross polarization levels.

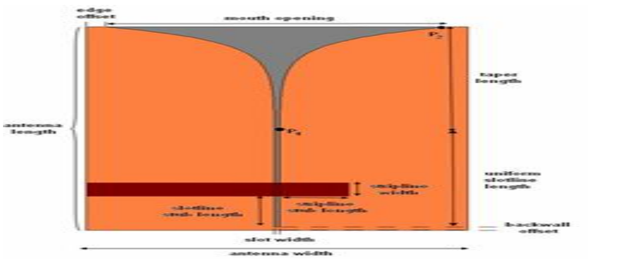


Fig. 2 – Designed Vivaldi antenna model and the parameters

However, the beamwidth of this type of transition increases with increasing frequency which is unacceptable when the beamwidth requirement of the design is too strict as in this study. Thus, stripline to slotline transition will be the most convenient choice with its beamwidth characteristic and enough bandwidth performance. The stripline to slotline transition bandwidth is improved using nonlinear stubs, radial or circular stubs, as described before. However, a uniform stub will be used to take the advantage of better radiation characteristics since the bandwidth requirements of the design are not so strict. The parameters and design of stripline to slotline transition will be detailed later in this chapter. The designed antenna model with the design parameters is given in Figure 2.

The stripline to slotline transition design starts with the choice of substrate material and thickness. Stripline width is calculated using the stripline characteristic impedance formulas given below.

$$Z_0=\frac{\eta_0}{2.0\pi\sqrt{\varepsilon_r}}\ln\left\{1.0+0.5\frac{8.0b}{\pi w'}\left[\frac{8.0b}{\pi w'}+\sqrt{\left(\frac{8.0b}{\pi w'}\right)^2+6.27}\right]\right\}$$

$$w'=w+\frac{\Delta w}{t}t \qquad \frac{\Delta w}{t}=\frac{\ln\left(\frac{5.0b}{t}\right)}{3.2}$$

$$Z_0=\frac{60}{\sqrt{\varepsilon_r}}\ \ln\left(\frac{4H}{0.67\pi\,(T+0.8W)}\right)\ \Omega$$

where,
Z_0 – characteristic impedance of the stripline (Ω)
η_0 – wave impedance of free space (Ω)
ε_r – relative permittivity of the dielectric
H – dielectric substrate thickness (mm)
T – stripline thickness (mm)
W – stripline width (mm)

Slotline design completes the design of stripline to slotline transition. Slotline is defined by its wavelength and the characteristic impedance which are calculated for specified substrate material dielectric constant, ε_r and thickness, H. The equations for ε_r = 2.2, 3.0, 6.5, 9.8 and $0.0015 \le W/\lambda_0 \le 1.0$. The following equations are in accordance with the design specified in this study.
For $2.22 \le \varepsilon_r \le 3.8$ and $0.0015 \le W/\lambda_0 \le 0.075$

$$\frac{\lambda'}{\lambda_0}=1.045-0.365\ln\varepsilon_r+\frac{6.3\left(\frac{W}{d}\right)\varepsilon_r^{0.945}}{\left(238.64+\frac{100W}{d}\right)}$$

$$-\left[0.148-\frac{8.81(\varepsilon_r+0.95)}{100\varepsilon_r}\right].\ln\left(\frac{d}{\lambda_0}\right)$$

$$Z_0 = 60 + 3.69 sin\left[\frac{(\varepsilon_r - 2.22)\pi}{2}.36\right] + 133.5\ln(10\varepsilon_r)\sqrt{\frac{W}{\lambda_0}}$$
$$+2.81[1 - 0.011\varepsilon_r(4.48 + ln\varepsilon_r)]\left(\frac{W}{d}\right)ln\left(\frac{100d}{\lambda_0}\right)$$
$$+131.1(1.028 - ln\varepsilon_r)\sqrt{\frac{d}{\lambda_0}}$$
$$+\frac{12.48(1 + 0.18ln\varepsilon_r)\left(\frac{W}{d}\right)}{\sqrt{\varepsilon_r - 2.06 + 0.85\left(\frac{W}{d}\right)^2}}$$

where,
λ' – slotline wavelength
λ_0 – operating wavelength
W – slotline width
d – dielectric substrate thickness
Z_0 – characteristic impedance of the slotline (Ω)
ε_r – relative permittivity of the dielectric

The complete antenna model is formed determining the uniform slotline length, tapered slotline length, taper rate, mouth opening and edge offset parameters. The complete antenna model with the air box, defined earlier, is given in Figure 3. The parameters to be determined in this section are evaluated regarding the effects of each parameter change in the actual return loss response and the *H*-plane radiation pattern (at f = 9.5 GHz, center frequency) simulating the antenna model using Ansoft ADS®. The antenna length parameter of stripline & slotline model section is reconsidered here using the results of taper length parameter study.

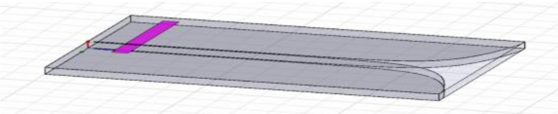


Fig. 3 – Complete antenna model in ADS®

The Vivaldi antenna parameters determined using the results of the stripline model, stripline & slotline model and antenna model are given in Table 1.

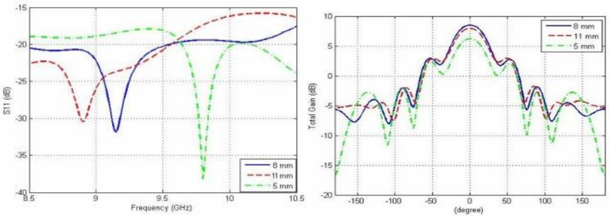
Table 1 – Final design parameters of the single Vivaldi element

Design Parameter	Value
Substrate Material	Rogers RT Duroid™ 5880
Substrate Thickness	3.14 mm
Stripline Width	2.5 mm
Stripline Length	24 mm
Stripline Distance to the Slotline Starting	4 mm
Slotline Width	0.5 mm
Antenna Length	61 mm
Antenna Width	40 mm
Backwall Offset	1 mm
Slotline Stub Length	4 mm
Taper Length	52 mm
Taper Rate	0.23
Mouth Opening	18 mm
Edge Offset	2 mm

4. RESULTS AND DISCUSSION:

4.1 Uniform Slotline Length

A quarter-wavelength stub is achieved expecting to obtain desired transition performance. An increase further from quarter wavelength results in degradation of return loss response as expected. In the same way, a decrease beyond quarter wavelength degrades radiation performance widening the main pattern and increasing 3 dB beamwidth. Return loss response and the radiation pattern of the antennas with uniform slotline lengths of S = 8 mm, S = 11 mm and S = 5 mm are given in Figure 4a.



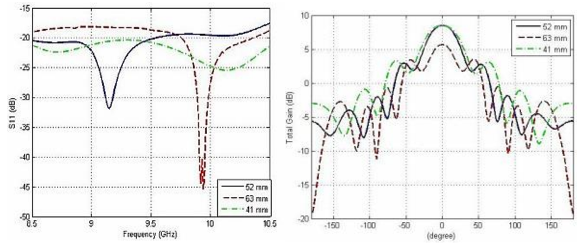
(a) (b)

Fig. 4 – (a) Return loss response with three different uniform slotline lengths. (b) H-plane radiation pattern with three different uniform slotline lengths (f = 9.5 GHz)

Uniform slotline length of S = 5 mm generates deeper nulls both in return loss and radiation pattern of the antenna as seen in Figure 4b. Uniform slotline lengths of S = 11 mm results in a fairly close response to that of S = 8 mm case. Antenna with uniform slotline length of S = 8 mm has a 3 dB beamwidth of 48º better than that of the antenna with S = 11 mm which is 50º. Thus, S = 8 mm is the most convenient choice for uniform slotline length of the design.

4.2 Taper

The taper design includes choosing the tapered slotline length and the taper rate (or flare angle). In fact, the sum of backwall offset length, uniform slotline length and tapered slotline length gives the antenna length. That is to say, determining antenna length, backwall offset length and the uniform slotline length also determines the tapered slotline length. It shall be in the order of a wavelength at the smallest operating frequency in order to get the desired gain and beamwidth performance. The bandwidth is also increasing with an increase in the taper length. The taper length is chosen as 52 mm regarding the antenna length of L = 61 mm of the stripline & slotline model. The return loss responses and radiation patterns of the antenna models with the taper length of LT = 52 mm, LT = 63 mm and LT = 41 mm are given in the Figure 5a, respectively.



(a) (b)

Fig. 5 – (a) Return loss response with three different Taper lengths. (b) *H*-plane radiation pattern with three different Taper lengths (f = 9.5 GHz)

In this case, the taper length of $LT = 63$ mm generates deeper nulls in the return loss response and radiation pattern as well as higher sidelobe levels. $LT = 41$ mm results in a 3 dB beamwidth of 56º which is fairly higher compared to $LT = 52$ and $LT = 63$ case. The taper length of $LT = 52$ mm, thus the antenna length of $L = 61$ mm, seems to be the most convenient choice regarding these results. However, the taper length will be evaluated again considering its effect on the Single Element Antenna radiation pattern.

The taper rate also has a significant effect on the return loss of the antenna. Decreasing the taper rate improves mid-band response effectively while the low- band performance is deteriorated. Thus, the lowest frequency of operation is increased and bandwidth is decreased in expense of improving mid-band return loss. Besides, beamwidth is also dependent on the taper opening rate. Beamwidth is getting narrower and sidelobe power levels are rising with increasing taper rate. Figure 5b below give the return loss response and radiation pattern for the taper rates of $R = 0.23$, $R = 0.20$ and $R = 0.26$.

5. CONCLUSION

The Vivaldi antenna, a type of TSA with its exponentially tapered profile, is observed in this Project. As a member of the class of TSA, Vivaldi antenna provides broad bandwidth, low cross polarization, and directive propagation at microwave frequencies. Vivaldi antennas are low cost and easy to fabricate due to printed circuit technology used for the construction of these antennas. Vivaldi Single Element Antennas are also small size and low weight enabling compact Single Element Antennas. The beamwidth and directivity of a Vivaldi antenna might be considerably improved varying the design parameters. Vivaldi antenna design parameters are investigated in this work. The effects of each antenna parameter on antenna impedance return loss response and reverse gain characteristics are simulated and observed.

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Конструкція компактної антени типу Вівальді для переносних пристроїв

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Зростаючий попит на переносні системи зв'язку передбачає створення малих, легких та високопродуктивних антен. У цій роботі описується проектування та впровадження малої антени типу Вівальді, адаптованої для тактичних діапазонів. Для досягнення компактності та гнучкості антена виготовлена з гнучкого матеріалу підкладки, який підтримує тіло людини, зберігаючи при цьому високу ефективність. Оцінюються такі фактори продуктивності, як коефіцієнт посилення, смуга пропускання, діаграма спрямованості, щоб гарантувати, що антена відповідає суворим критеріям для пристроїв, що переносяться. Мініатюрна конструкція мінімізує розмір без шкоди для продуктивності. Результати моделювання та експериментів демонструють, що антена забезпечує стабільні характеристики випромінювання та хорошу ефективність. Досліджено вплив втрат на відбиття, КСХН, коефіцієнта посилення та діаграми спрямованості на проектування одноелементної антени. Представлено та розглянуто результати моделювання, виконаного за допомогою Ansoft ADS, програми моделювання високочастотного електромагнітного поля.

Ключові слова: Бездротовий зв'язок, Переносні пристрої, Антена типу Вівальді, КСХН, Тактична антена.