Wideband Dual Vivaldi nano-antenna with high radiation efficiency over the infrared frequency band

Zeev Iluz and Amir Boag

School of Electrical Engineering, Tel Aviv University, Tel-Aviv 69978, Israel

Abstract — Down scaling the well-known concept of metallic antennas to the optical frequencies offers unique advantages for novel photonic applications. One of the promising new applications is energy harvesting, using a rectenna. A key building block in such a system is an efficient antenna. A dual-Vivaldi nano-antenna is proposed to demonstrate the possibility of wideband operation at Infra-Red (IR) frequencies. According to our numerical results this nano-antenna has both high radiation efficiency and good impedance matching properties over a wide frequency band (more than 122%) in the IR frequency band. The design is based on the well-known Vivaldi antenna placed on Quartz substrate, but operating as a pair instead of a single element. Such pair of Vivaldi antennas oriented in opposite directions produces the main lobe in the broadside direction (normal to the axes of the antennas), rather than the usual peak gain along the axis (end-fire) of a single Vivaldi antennas.

Index Terms — Nanophotonics, Vivaldi antennas, Ultra wideband antennas, Nanostructured materials, Rectennas.

I. INTRODUCTION

Energy harvesting at optical frequencies attract a lot of research attention in the recent years. Using a rectenna device is one of the promising approaches. A rectenna is a rectifying antenna, with non-linear load at the antenna terminals, which is used to directly convert optical energy into DC electricity. High efficient system requires both efficient antenna and rectification process.

Many of the studies in the field of optical antennas reported either low radiation efficiency [1], or high efficiency limited to a narrow frequency band of operation [2]. In fact, no antenna configurations which are both efficient and broadband at IR frequencies have been presented so far. We believe that taking into account the metal properties, i.e., the complex index of refraction and, especially, the resulting skin depth is the key to devising efficient broad-band antennas.

At the radio frequencies (RF), typically, metallic antenna thickness is significantly larger than the skin depth. Thus, overly thin conductors with high resistance leading to low radiation efficiency are avoided. However, in contrast to the trend in the RF band, over the IR range the skin depth does not decrease monotonically as the frequency increases. We can calculate the skin depth by using its definition: \( \delta = 1/\alpha \) where \( \alpha \) is the real part of the complex propagation constant (also known as the absorption coefficient). For example in gold [3], the skin depth remains at roughly 13 nm over a large part of the IR band and even increases at the beginning of the visible spectrum. The skin depth thickness results in the conclusion that any nano-antenna element made out of gold for the IR frequency band needs to be at least 40-50 nm thick in order to have high radiation efficiency.

This work objective is to demonstrate the feasibility of Ultra Wide Band (UWB) nano-antenna operation at IR frequencies. To that end, we design a traveling wave nano-antenna that is broad-band in terms of both impedance matching and radiation efficiency. In traveling wave antennas, as opposed to resonant ones, the transition from waveguiding to radiation occurs gradually through a tapered geometry, thus, leading to a wide bandwidth and improved efficiency.

II. THE DUAL VIVALDI ANTENNA GEOMETRY

The classical Vivaldi antenna is basically a slot antenna with an exponential taper profile, designed to have impedance matching over an UWB of frequencies and end-fire radiation pattern [4]. The upper part of the basic Vivaldi antenna geometry in the \( x-z \) plane is described by:

\[
x = C_1 \exp(Rz) + C_2
\]

where \( R \) is an opening rate and the constants \( C_1 \) and \( C_2 \) are defined by

\[
C_1 = \frac{x_{\text{end}} - x_{\text{start}}}{\exp(Rz_{\text{end}}) + \exp(Rz_{\text{start}})}
\]

\[
C_2 = \frac{x_{\text{start}} \exp(Rz_{\text{end}}) - x_{\text{end}} \exp(Rz_{\text{start}})}{\exp(Rz_{\text{end}}) + \exp(Rz_{\text{start}})}
\]

with \( (x_{\text{start}}, z_{\text{start}}) \) and \( (x_{\text{end}}, z_{\text{end}}) \) denoting the coordinates of the starting and ending points of the taper profile, respectively. The lower part of the antenna is a mirror image of the upper one, together creating a finite traveling wave radiating configuration.

However, when fabricated on a substrate, the end fire radiation of conventional Vivaldi antennas, i.e., at grazing to the surface, is not very convenient for optical applications. Here, we present a dual Vivaldi antenna configuration. Our
approach involves the use two end-fire antennas, placed opposite to one another, in order to get a peak gain at the antenna broadside direction (normal to the $x-z$ plane in our coordinate system). This goal can be achieved if each antenna cancels its dual's end-fire radiation, while the broadside fields of the two antennas add up coherently. The resulting Dual Vivaldi antenna can be fabricated as a single metallic layer on planar substrate and has a bi-directional radiation pattern normal to the substrate surface. In contrast, directive 3D Yagi-Uda [5] or nanoloop [6] antennas involve considerably more complicated multi layered structures.

Each of the Vivaldi antennas is fed by integrated parallel plate waveguide, with a gap of $W_1 = 2x_{\text{start}} = 25 \text{ nm}$ and thickness of $h = 120 \text{ nm}$. The parallel plate impedance is approximately determined as $Z_0 = \eta W_1 / h = 78.5 \Omega$ [7], where $\eta = 377 \Omega$ is the free space impedance. A relatively wide 25 nm gap is selected to facilitate fabrication in a standard E-beam lithography based process. The thickness needs to be several times larger than the skin depth at IR, so it was chosen to be 120 nm, i.e., about ten times the skin depth of gold.

The impedance matching is achieved by opening the slot profile at the optimal rate. The antenna was designed to operate from 0.7 $\mu\text{m}$ to 3.25 $\mu\text{m}$, with opening rate $R = 0.002 \text{ nm}^{-1}$, length $L = z_{\text{end}} - z_{\text{start}} = 0.25 \mu\text{m}$ and width of the taper slot $W_2 = 0.5 \mu\text{m}$. The design parameters of the dual Vivaldi nano-antenna made of gold and deposited on Quartz substrate are shown in Fig. 1. In our simulations, the antenna is placed in the center Quartz substrate with lateral dimensions of 2x2 $\mu\text{m}$ and thickness of 1 $\mu\text{m}$.

![Fig. 1. (color online) The dual Vivaldi nano-antenna top view geometry.](image)

Feeding the dual Vivaldi by parallel plate waveguides allows us to use wider gaps as compared to the gap required in a dipole like antenna. In fact, the theoretical limitation on $W_1$ is being less than half the wavelength at the highest frequency of operation in order to support only the transverse electromagnetic (TEM) mode and not the higher modes. For future applications, we will prefer to keep $W_1$ as small as feasible in the fabrication process, since increasing $W_1$ reduces the electric field enhancement when the antenna operates in the receive mode. Antenna parameters $R$, $L$, and $W_2$ are used to tune the radiation pattern to have the peak gain at the antenna broadside and to ensure impedance matching between the antennas and the parallel plate waveguide.

III. SIMULATION RESULTS

The simulation was performed by using commercial software CST MWS [8], with the finite elements frequency domain solver. The gold complex index of refraction (N, K) database at the IR frequencies was defined in the simulation so that the correct measured index of refraction value was used at each frequency point. Both parallel plate waveguide gaps were excited coherently and in phase, using ports across the gaps.

The simulated input impedance of each port is presented in Fig. 2.

![Fig. 2. (color online) The dual Vivaldi input resistance and reactance.](image)

The return loss of the dual Vivaldi antenna is better than -9.5 dB for the range of 0.7 $\mu\text{m}$ to 3.25 $\mu\text{m}$ (129% impedance bandwidth). The antenna does not have a single resonance behavior such as a dipole antenna, but rather multi resonance behavior characteristic for finite size traveling wave configurations. It can be seen from Fig. 2 that the input resistance (the real part of the impedance) is relatively constant (at around 100 $\Omega$), and the input reactance (the imaginary part) oscillates around zero in the frequency band of operation.

However well behaved, the return loss is not sufficient to fully characterize the nano-antenna performance. The radiation efficiency, defined as the radiated to accepted (input) power ratio, is a critical parameter due to the losses in metals at IR frequencies. In our configuration, the radiation efficiency remains higher than 85% for frequencies ranging from
0.78 μm to 3.23 μm (122% efficiency bandwidth), as presented in Fig. 3(a).

Due to the Quartz substrate that acts like a lens, the far field pattern is not symmetric and the higher directivity is in the Quartz direction. At the lower wavelengths the Quartz substrate changes the antenna pattern and the peak gain is shifted from the antenna broadside. The maximum realized gain (including the mismatch loss) at the antenna broadside direction reaches 6 dBi, and peak gain is 7 dBi (see Fig. 3(b)). These values are very high compared to the previous results reported for nano-antennas, especially if we take into account that this is a single layer structure, without ground plane. Thanks to the reciprocity theorem for an antenna comprising isotropic materials, the radiation pattern of such an antenna is equal to its receiving pattern.

IV. CONCLUSION

In summary, we have reported numerical results for a Dual Vivaldi nano-antenna. The high efficiency can, in our opinion, be attributed to the concentration of the field in the gap between the antenna terminals as well as to the gradual transition from the wave guiding to radiation. The broadside peak radiation allows for integration of dual Vivaldi antennas in planar configurations, using E-beam lithography process. The Dual Vivaldi antenna poses fewer fabrication restrictions as compared to dipole and bow-tie antennas, especially in terms of the gap size between the antenna terminals.

REFERENCES

射频和天线设计培训课程推荐

易迪拓培训(www.edatop.com)由数名来自于研发第一线的资深工程师发起成立，致力并专注于微波、射频、天线设计研发人才的培养；我们于2006年整合合并微波EDA网(www.mweda.com)，现已发展成为国内最大的微波射频和天线设计人才培养基地，成功推出多套微波射频以及天线设计经典培训课程和ADS、HFSS等专业软件使用培训课程，广受客户好评；并先后与人民邮电出版社、电子工业出版社合作出版了多本专业图书，帮助数万名工程师提升了专业技术能力。客户遍布中兴通讯、研通高频、埃威航电、国人通信等多家国内知名公司，以及台湾工业技术研究院、永业科技、全一电子等多家台湾地区企业。

易迪拓培训课程列表：http://www.edatop.com/peixun/rfe/129.html

射频工程师养成培训课程套装
该套装精选了射频专业基础培训课程、射频仿真设计培训课程和射频电路测量培训课程三个类别共30门视频培训课程和3本图书教材；旨在引领学员全面学习一个射频工程师需要熟悉、理解和掌握的专业知识和研发设计能力。通过套装的学习，能够让学员完全达到和胜任一个合格的射频工程师的要求…

课程网址：http://www.edatop.com/peixun/rfe/110.html

ADS学习培训课程套装
该套装是迄今国内最全面、最权威的ADS培训教程，共包含10门ADS学习培训课程。课程是由具有多年ADS使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了ADS在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用ADS，迅速提升个人技术能力，把ADS真正应用到实际研发工作中去，成为ADS设计专家…


HFSS学习培训课程套装
该套课程套装包含了本站全部HFSS培训课程，是迄今国内最全面、最专业的HFSS培训教学套装，可以帮助您从零开始，全面深入学习HFSS的各项功能和在多个方面的工程应用。购买套装，更可超值赠送3个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您学习更加轻松顺畅…

课程网址：http://www.edatop.com/peixun/hfss/11.html
专注于微波、射频、天线设计人才的培养
网址：http://www.edatop.com

### CST 学习培训课程套装

该培训套装由易迪拓培训联合微波EDA网共同推出，是最全面、系统、专业的CST微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习CST微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送3个月免费学习答疑...


### HFSS 天线设计培训课程套装

套装包含6门视频课程和1本图书，课程从基础讲起，内容由浅入深，理论介绍和实际操作讲解相结合，全面系统的讲述了HFSS天线设计的全过程。是国内最全面、最专业的HFSS天线设计课程，可以帮助您快速学习掌握如何使用HFSS设计天线，让天线设计不再难...

课程网址：http://www.edatop.com/peixun/hfss/122.html

### 13.56MHz NFC/RFID 线圈天线设计培训课程套装

套装包含4门视频培训课程，培训将13.56MHz线圈天线设计原理和仿真设计实践相结合，全面系统地讲解了13.56MHz线圈天线的工作原理、设计方法、设计考量以及使用HFSS和CST仿真分析线圈天线的具体操作，同时还介绍了13.56MHz线圈天线匹配电路的设计和调试。通过该套课程的学习，可以帮助您快速学习掌握13.56MHz线圈天线及其匹配电路的原理、设计和调试...


### 我们的课程优势：

※ 成立于2004年，10多年丰富的行业经验，
※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求
※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

### 联系我们：

※ 易迪拓培训官网：http://www.edatop.com
※ 微波EDA网：http://www.mweda.com
※ 官方淘宝店：http://shop36920890.taobao.com