A Design of Terahertz Parallel Plate Dielectric Waveguide with Signal Line inserted for Ballistic Deflection Transistor Travelling Wave Amplifier

H. Wang¹, ², R. Knepper², N. Hossain¹, P. Marthi¹, J-F. Milithaler¹ and M. Margala¹

¹. Department of Electrical and Computer Engineering, University of Massachusetts, 1 University Ave., Lowell, MA 01854
². Department of Electrical and Computer Engineering, Boston University, 8 Saint Marys Street, Boston, MA 02215

Huan_Wang@student.uml.edu

Abstract. In this paper a new waveguide design is proposed to be implemented as part of Ballistic Deflection Transistor (BDT) Traveling Wave Amplifier Design. The BDT is designed to be operated in the Terahertz regime. Due to its relatively low transconductance ($g_m=200\mu A/V$), the entire structure will consist of ten stages, with 15 BDTs/stage, to reach a total gain of 30mA/V. In this case, the total length of the transmission line will be more than 400µm. We did the investigation for different structures and materials of the transmission line. For our Parallel Plate Dielectric Waveguide with Signal Line inserted (PPDWS) design, we are able to get an average loss of 0.46dB/mm at 0.8-1.4THz from ANSYS HFSS simulation. The return loss for input and output are better than -20dB at 0.8-1.7THz. Although it is designed for our future travelling wave amplifier, it can also be used for various other THz frequency applications.

1. Introduction

With the rapid growth in research and development of Terahertz (THz) devices, people are becoming more and more interested by applying THz devices into more applications such as imaging [1], telecommunications [2], biotechnology [3], astronomy [4]. Different kinds of devices have been introduced to be operated in THz regime for those purposes.

Our group has utilized a THz device called the Ballistic Deflection Transistor (BDT). This planar device is fabricated in an InGaAs/InAlAs heterostructure on InP substrate and consists of six terminals: a source, a top drain which pulls electrons, two output left and right drains and two lateral gates [5]. A negative bias applied on one gate will deplete the adjacent channel and, with the help of a strategically placed deflector, will steer electrons toward the opposite direction. This component provides a unique symmetric transfer characteristic which depends on geometry and polarization [6, 7]. More details can be found in [8].

Because of the low transconductance of the BDT, we would need at least ten stages, each stage comprised of 15 BDTs in parallel [9] to reach a gain of 3 mA/V per stage. A nearly lossless THz
transmission line over 400 \( \mu \text{m} \) in length should be implemented into the amplifier design. However, for THz waveguide, neither conventional metal waveguides nor dielectric fibers are able to transmit this kind of very high frequency signal over a very long distance. The main issue is the high loss for the metal and high absorption efficiency for the dielectric materials in the THz regime [10]. The development of a THz transmission line will play a very important role in the designs of future THz applications.

In our own research, we have tried to implement the conventional coplanar waveguide (CPW) topology to design the THz waveguide, but the CPW is very lossy in the THz region and this is a key issue for THz CPW design. Over the last ten years, varieties of THz waveguide have been proposed such as non-radiative dielectric (NRD) waveguide [11], parallel plate waveguide (PPW) [12, 13], and parallel plate dielectric waveguide (PPDW) [14]. Both NRD and PPW are operated at higher transmission modes, but PPDW works at the fundamental TE\(_{10}\) mode. What’s more, PPDW has a simpler structure and very low loss over a long distance in the THz region. However, the PPDW is not able to be directly connected with semiconductor devices. Thus, a new structure called Parallel Plate Dielectric Waveguide with an inserted signal conductor wire (PPDWS) is introduced.

### 2. Parallel Plate Dielectric Plate Design

The PPDWS is presented in Fig 1. The structure of the PPDWS consists of a rectangular dielectric strip with a height of \( h \) and width of \( w \). The center dielectric strip is sandwiched between two metal plates as the ground planes. A metal conductor wire is inserted in the center of the dielectric strip.

The metal gold, with a high conductivity \((\sigma=4.42 \times 10^7 \text{ S/m})\), high melting point, resistant to oxidation compared to silver and widely implemented as the material for high frequency applications has been chosen for metal planes and the signal line. The dielectric constant of the center strip should be greater than the outside dielectric in order to keep the radiation energy inside the dielectric strip without any leakage from the dielectric strip. Furthermore, in the fabrication process for this type of structure we need supporting material to fill the gaps to support the upper metal plane, leading to a choice of \( \text{Si}_3\text{N}_4 \) \((\varepsilon_r=9.5, \tan\delta=2 \times 10^{-5})\) for the center dielectric strip and \( \text{SiO}_2 \) \((\varepsilon_r=3.7, \tan\delta=0.001)\) for the remainder.

The idea of the signal line derives from the conventional CPW design. In order to be connected with the BDT, we cannot use the PPDW directly. By taking the signal line from CPW and inserting it into the dielectric strip will directly connect the waveguide with the transistor’s channel, which in this case is 300nm; as a result, the width of the signal line is equal to the channel width of the BDT \((A=300\text{nm})\). The thickness \((T)\) of the signal line will be determined by the skin effect thickness given by the following equation:

\[
\delta = \sqrt{\frac{2\rho}{2\pi f \mu \varepsilon_0}}
\]
f represents the operating frequency which is 1THz, ρ represents the resistivity of gold, μ_μ is the relative permeability of gold and μ_μ is the permeability of free space equal to 4×10⁻⁷ H/m. Assuming $T \geq 3f$ which leads to $T \geq 297$ mm, in this design 300 nm is applied as the thickness for the signal line. In Fig 1, the thickness of the dielectric (W=H=100 µm) will greatly influence the performance of the waveguide, is explained below in simulation results. The width of the metal plane is equal to 3W=300 µm, which will prevent the radiation leakage from two sides. The thickness of the metal plane is 500 nm, which is good for fabrication.

3. Simulation Results and Analysis

Fig 2. (a) Top view (b) Side view of Electric Field Distribution of PPDWS at 1THz (1mm long)

Fig 2 presents the field confinement of the PPDWS at 1THz. It clearly shows the TE10 mode in the electric field distribution. After propagating for the length of the transmission line, the waves inside almost remained unchanged, and the blue area shows that all the energy is locked inside the dielectric area and that no radiation is going outside.

Fig 3. (a) Return Loss of a 50 µm thick dielectric strip at 1.54-2 THz (1 mm long) (b) Return Loss of the 100µm thick dielectric strip at 0.8-1.5 THz (1 mm long)

Fig 3. shows two plots of the S-parameter simulation results from HFSS. Comparing the results from (a) and (b), average total transmission loss for a 50µm thickness is 1.4976 dB/mm at 1.5-2 THz (best
bandwidth for the lowest transmission loss) with an average S11 of -17.7dB, while for a 100 µm thickness it is only 0.46 dB/mm at 0.8-1.5 THz, which is 1 dB better. We can state that the loss is greatly influenced by the thickness of the dielectric. By increasing the thickness of dielectric strip, we are able to reduce the loss of the transmission line, but it will also lead to the increase of the effective permittivity and power refinement [15]. When taken into consideration in the fabrication possibility, the 100 µm is the optimum thickness for the dielectric strip.

4. Conclusion
A new design of transmission line using the PPDWS technique is developed to be operated in the Terahertz band and integrated with THz BDT travelling wave amplifier. For a 100µm thick PPDWS has an average loss as low as 0.46 dB/mm at a broad frequency band at 0.8-1.5 THz. And the return loss at its input is below -20 dB for the frequency band. What’s more, compared with the PPDW design, the PPDWS is able to be connected to the device directly. The operating frequency is also much higher and wider than with the PPDW structure. As a result PPDWS is an excellent candidate for the THz BDT travelling wave amplifier design and also has a great potential in other THz RF applications.

References
[1] J.F.Fedrici et al., “THz imaging and sensing for security applications, explosive weapons and drugs,” Semicond. Sci. & Tech., No.20, S266-280, 2005
[2] I. F. Akyildiz et al., “Terahertz band: Next Frontier for wireless communications,” Physical Communication 12 (2014) 16-32
[3] X. Yang et al., “Biomedical Applications of Terahertz Spectroscopy and Imaging,” Trends in Biotech., Vol.34, No.10, Oct.2016
[4] C. Kulesa, “Terahertz Spectroscopy for Astronomy: From Comets to Cosmology,” IEEE Trans. Terahertz Sci. & Tech., Vol.1, No.1, September. 2011
[5] Q. Diduck et al., "A Room Temperature Ballistic Deflection Transistor For High Performance Applications," International Journal of High Speed Electronics and Systems, vol. 19, pp. 23-31, 2009.
[6] V. Kausal et al., "A Study of Geometry Effects on the Performance of Ballistic Deflection Transistor," IEEE Transactions on Nanotechnology, vol. 9, pp. 723-733, 2010.
[7] M. Margala et al., "Current transport modeling and experimental study of THz room temperature ballistic deflection transistors," J. Phys. Conf. Ser., vol. 193, p. 4, 2009.
[8] J.-F. Millithaler et al. "Optimization of Ballistic Deflection Transistors by Monte Carlo Simulations," J. Phys.: Conf. Ser., 647, 012066, (2015)
[9] M. Margala et al., “Ballistic deflection transistors and their application to THz amplification”, J. Phys.: Conf. Ser. 647, 012020 (2015)
[10] H. Bao et al., “Dielectric tube waveguides with absorptive cladding for broadband, low-dispersion and low loss THz guiding”, Scientific Report 5, Article No.7620 (2015)
[11] T. Yoneyma, “Nonradiative Dielectric Waveguide”, Infrared and Millimeter Waves, Vol.11, Ch.2, K.J. ButtonEd. New York: Academic Press, 61-98 (1984)
[12] R. Mendis and D. Grischkowsky, “Undistorted guided-wave propagation of subpicosecond terahertz pulses”, Opt. Lett. 26(11), 846-848(2011)
[13] R. Mendis, “Guided-wave THz time-domain spectroscopy of highly doped silicon using parallel-plate-waveguides”, Electron. Lett. 42(1), 19-21 (2006).
[14] L. Ye et al. “A novel broadband coaxial probe to parrelle palte dielectric waveguide transition at THz frequency”, Opt. Express., Vol.18, No.21 (2010)
[15] L. Cao et al. “Comparison and optimization of dispersion,and losses of planar waveguides on benzocyclobutene (BCB) at the frequencies:coplanar waveguide (CPW), microstrip,stripline and slotline”, Progress in Electromagnetic Research B, Vol.56, 161-183 (2013)