Development of novel waveguides in the terahertz (THz) region

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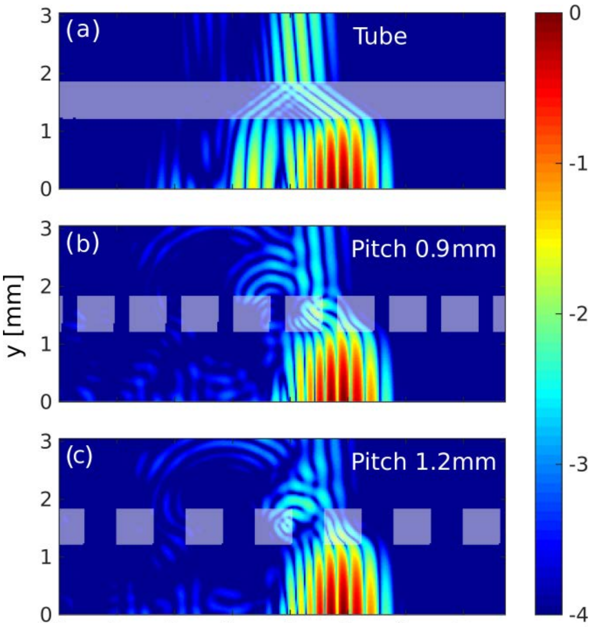
Terahertz Science

Terahertz (THz) radiation, often referred to the frequency range from 0.1 to 10 THz, is the focus of an active and fast growing research community. However, this frequency range located in the electromagnetic spectrum between the microwave band and infrared band, was known as the “THz-gap” until the late 1980's. A lack of available coherent sources and detectors rendered this frequency range inaccessible. The breakthrough was achieved with the generation of THz-radiation by means of femtosecond laser pulses in the visible or near-infrared range. The generation is usually achieved by either photo-conductive antennas or nonlinear crystals: while a biased photo-conductive antenna emits THz-radiation due to a time dependent photo-current induced by a femtosecond laser pulse, a nonlinear crystal hit by a femtosecond pulse generates a THz-pulse by difference frequency generation. Further development of THz-detectors and THz-sources like the introduction of a quantum cascade laser suitable for Terahertz frequencies provided the access to a vast variety of THz applications. In the past two decades a Terahertz technology in various fields like information and communications technology, biology and medical sciences, non-destructive evaluation and homeland security were established. Moreover, Terahertz radiation is suitable to study fundamental processes present in this frequency range like e.g. phonon excitation as well as inter-band transitions in condensed matter and rotational transitions of molecules in gases.

Terahertz Waveguides

However, to take advantage of these promising applications and to realize bench top THz devices, waveguides capable of guiding broadband THz radiation with low loss and low dispersion are essential. A first approach to utilize the well-known waveguides from microwave or near-infrared systems, namely circular/rectangular metallic waveguides and dielectric fibers, proved to be impractical. Novel waveguide designs were necessary to overcome the increasing ohmic losses at metal surfaces and the high dielectric absorption in the Terahertz frequency range. Although an extensive research over the past ten years led to a number of new waveguide designs and materials, there is still a high demand on further improvements and investigations.



FDTD simulation of a THz pulse propagating in a) a dielectric tube waveguide and b)-c) a 3D-printed dielectric helical waveguide with different pitches

The intention of our work is to contribute to the development of novel single-mode waveguides with low loss and low dispersion. The picture shows the electric field energy density of a THz pulse propagating through three different waveguides: a dielectric tube, and two different dielectric helices. The THz pulse is propagating in positive z-direction, and the grey areas are the dielectric material. The centre axis of the waveguide is just below the x-axis of each sub-figure. The novel waveguide designs are experimentally investigated with a THz time-domain spectroscopy setup based on photo-conductive antennas. Moreover, a comprehensive numerical study based on the finite-difference time domain (FDTD) method is performed to support the measurements. The basic idea behind any FDTD method is to approximate the continuous space derivatives and time derivatives of the time dependent Maxwell's equation with discrete finite-differences. This is necessary as the boundary conditions are so complicated that there is no analytical solution. The time-domain method, compared to a frequency-domain method, provides the advantage that we can investigate the broadband frequency response of our waveguides with only a single simulation. All FDTD simulations performed in this work are done with the Unix-based open-source software "MIT Electromagnetic Equation Propagation" (MEEP). It is important to note that our simulations are performed in 3D as our waveguides do not have a uniform cross-section and we therefore cannot employ the 'usual' software packages used for more traditional waveguides. The extensive numerical study of the waveguides is indispensable for the development of high performance THz waveguides. The simulations provide detailed insight into the guidance mechanism of the waveguides and facilitate the design process for the most efficient THz waveguides as different configurations can be compared easily.

3D FDTD simulations of THz waveguides on the NeSI Pan cluster

The New Zealand eScience Infrastructure (NeSI) Pan cluster provides us the only possibility to perform our simulations with the required resolution. Our 3D FDTD simulations involve extremely time consuming calculations and have such a high memory demand that an implementation on a normal desktop computer is not feasible. A typical three dimensional simulation for a 100mm long waveguide is running on up to a 100 cores and requires approximately 400GB of memory. A typical processing time for such a job is about 30 hours. Moreover, the Cluster allows us to investigate multiple waveguide designs simultaneously which provides a great ease for our research. As can be seen in the picture, a slightly different pitch for the helix can result in quite different losses. We have also numerically investigated metal helices with and without a dielectric coating using Pan cluster.

Results and future work

Recent work facilitated by the NeSI Pan cluster includes our investigation of broadband guidance of THz radiation in both metallic and 3D printed dielectric helical waveguides. Each type of waveguide has been presented at the annual International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) in Tucson (USA) and Hong Kong (CHN). The work is also published in the corresponding conference proceedings. Future work will concentrate on further studies of these waveguides and the development of sophisticated high performance waveguides for the THz frequency band and their application.