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DIELECTRIC LOADED THz WAVEGUIDE EXPERIMENTALLY OPTIMIZED BY DISPERSION MEASUREMENTS

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Abstract

Emerging high power THz sources pave the road for THz-driven acceleration of ultra-short bunches, and enable their manipulation for diagnostic purposes. Due to the small feature sizes of THz-guiding devices new methods are necessary for their electromagnetic characterization. A new technique has recently been developed which characterizes THz waveguides with respect to their dispersion relations and attenuation. Here, the method is applied to circular waveguides, partially filled with polymer capillaries of different thicknesses, to find a suitable size for THz driven streaking at 287 GHz. Further, rough 3d-printed metallic waveguides are measured to study the effect of roughness on attenuation and phase constant. In general, additive manufacturing techniques show promise for advanced integrated designs of THz driven structures.

INTRODUCTION

In recent years, there has been growing interest in Terahertz (THz) radiation as driving source for particle accelerators [1–5] due to the availability of emerging laser-based high-power sources [6, 7] and promises in supporting higher field gradients than conventional RF-driven structures. Beyond acceleration, THz driven structures are also studied for beam manipulation, for instance, as transverse deflecting structures [8–12] to measure the bunch length with high resolution. One potential design is based on dielectric loaded waveguides which profit from higher streaking voltage and reduced non-linearities of the field distribution [13, 14]. Due to the small feature size on mm-scale, established characterization methods from radio-frequency structures are difficult to apply. Laser-based techniques partially take over, for instance, in measuring waveguide dispersion [15]. Alternatively, a new RF-based approach has been proposed by the authors to characterize THz structures by their dispersion [16]. The method does not rely on the integrated phase shift, but is able to provide local information within the waveguide.

In the present work, the inner radius of a dielectric loaded waveguide, formed by inserting a polymer capillary in a circular metallic waveguide, is adjusted to match synchronous phase velocity, $v_{ph} = c$, to the design frequency of 287 GHz. The design frequency is based on a THz generation setup located at the REGAE facility [13, 17] at DESY. Frequency tunability of the THz source restricts the waveguide's phase synchronous mode to 286 GHz to 288 GHz.

Further, the dispersion of pure metallic waveguides fabricated by selective laser melting (SLM) is measured. Due to the rough surface the diameter of the cross-section can only be estimated by microscopy. The measured dispersion allows to determine an effective diameter due to the electromagnetic response.

The first chapter briefly recapitulates the experimental setup and the analysis method. In the second chapter, measurements on a metallic waveguide equipped with polymer capillaries are presented. Aiming for a specific design frequency at which the mode propagates synchronously with a potential bunch, the optimal capillary loading is determined. Afterwards, experiments on 3D printed, pure metallic waveguides are shown. Finally, an outlook is given towards an accelerator-based experiment.

EXPERIMENTAL SETUP AND NETWORK MODEL

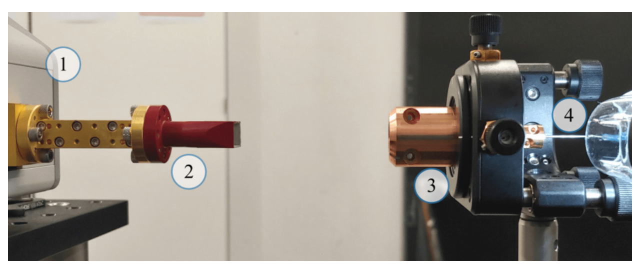

Figure 1: Experimental setup. (1) Extender waveguide port (2) Horn antenna (3) Integrated horn-waveguide structure (4) Movable obstacle. Reproduced from Ref. [16]

The main part of the experimental setup is shown in Fig. 1. Scattering parameters are measured via a Rohde & Schwarz ZVA67 vector network analyzer (not shown) to which a frequency extender ZC330 is connected, spanning the band from 220 GHz to 330 GHz. A pyramidal horn antenna is attached to the waveguide port of the extender. The waveguide under test, which is monolithically integrated with its conical horn coupler, is mounted in a distance of about 7 cm. A reflecting obstacle is placed inside the waveguide from the other side. The obstacle is mounted on a linear translation stage to scan the reflection position in sub-wavelength steps. The position sweep shifts the phase of S_{11} of the device under test. Multiple reflections between the reference port and the test device distort the S-parameter $S_{11}^{(m)}$ measured

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by the VNA. An error network model has been derived to describe the response. The out-coupling horn, the free space section, and the in-coupling horn are combined into a single error network. The measured response of the total system is modelled as

$$S_{11}^{(m)}(f,l) = a + \frac{b}{e^{-2(\alpha+i\beta)l} - c}, \qquad (1)$$

where $\gamma = \alpha + i\beta$ is the propagation constant, and a, b, c are parameters combining the error terms, like directivity, source match and reflection tracking. All parameters are frequency dependent. To determine the dispersion relation of the integrated waveguide, the measured set $S_{11}^{(m)}(l; f)$ is analyzed independently for each frequency point. The model Eq. (1) is fitted via a non-linear least-squares method to each $S_{11}^{(m)}(l)$, where eight real unknown parameters are taken into account. The error terms are complex-valued. If the scanning range is not sufficient to resolve the attenuation, the parameter space can be reduced to seven unknowns since $\alpha = 0$ is assumed.

WAVEGUIDES LOADED WITH 3D PRINTED POLYMER CAPILLARIES

The split-block waveguide presented in [16] is successively loaded with six additively manufactured polymer capillaries. The waveguide has an experimentally determined radius of (0.66 ± 0.01) mm. The capillaries are printed by the ASIGA MAX X UV385 DLP printer. Moiin Tech Clear has been chosen as resin and its permittivity has been measured in advance, $\varepsilon_r = 2.92 \pm 0.02$. Using the design frequency, outer radius and permittivity, the required inner radius a to achieve $v_{ph} = c$ is calculated analytically. Due to the uncertainty in ε_r and potential air gaps between capillary and metallic wall, the measured phase synchronous frequency may deviate substantially. Therefore, the capillaries have been printed with varying radii close to the design value,

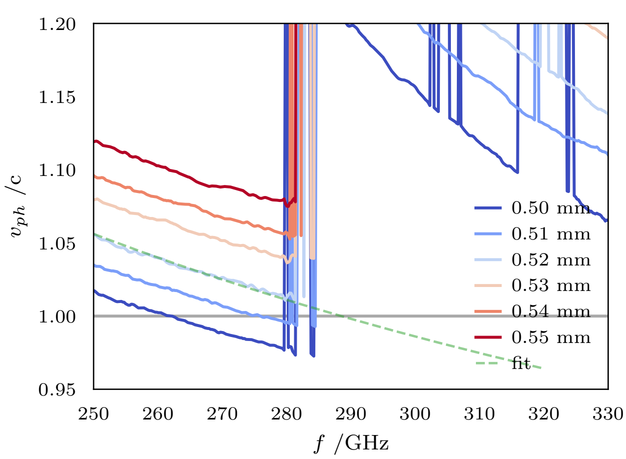


Figure 2: Phase velocity dispersion of the dielectric loaded waveguide with polymer capillaries of different size as lining. The fit of the third measurement approximates $v_{\mathrm{ph}}(f)$ with Eq. (2). The orange region marks the goal frequency band.

covering the range from 0.5 mm to 0.55 mm. The actual size may deviate due to shrinkage. But the goal is to optimize the parameters adjustable for the printing process.

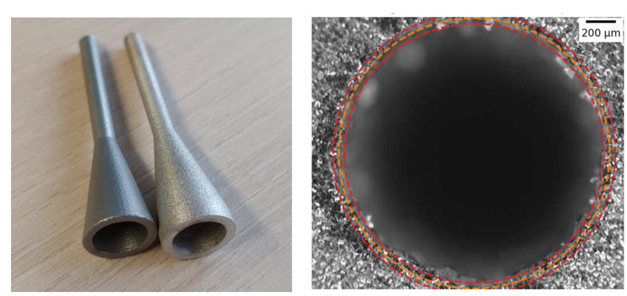
Figure 2 shows the measured phase velocity dispersion for the six waveguides of different polymer size, focusing on the frequency range and phase velocity range of interest. First, it is observed that in all waveguides higher order modes are predominantly excited above ≈ 280 GHz. The current model in Eq. (1) assumes a single-mode excitation which is why it is the modes are not separated. Further, the first two measurements, $a = 0.5$ mm and $a = 0.51$ mm, show a crossing of the speed of light dispersion already below the higher order mode threshold. The fundamental HE_{11} mode propagates phase synchronously with a hypothetical ultra-relativistic beam at (262 ± 2) GHz and (276 ± 2) GHz. Both cases demonstrate the feasibility of the method, but the frequencies lie outside the tunability range of the dedicated THz source. Although the third dispersion line shows the jump to a higher order mode, its course indicates a crossing of $v_{ph} = c$ by extrapolation from the data points below the jump. A non-linear least-squares fit is applied to the truncated data, using the approximate model

$$v_{ph}(f) = p_0 + \frac{p_1}{f}, \qquad (2)$$

where p_0, p_1 are the fit parameters. This approximation is valid in the vicinity of $v_{ph} = c$ and the thickness of the dielectric $b - a$ must be smaller than the inner radius. The fit is plotted in Fig. 2 and a crossing of $v_{ph} = c$ is found in the frequency range of interest, close to 287 GHz. Although the higher order mode is mainly excited, it is reasonable to assume that the fundamental mode is also excited substantially. The capillary with $a = 0.52$ mm mounted in the metallic waveguide is suitable for future experiments involving THz-beam interaction.

METALLIC 3D PRINTED WAVEGUIDES

The experimental method is also applied to characterize horn-waveguide devices fabricated by additive manufacturing of steel (316L), also called metallic 3D-printing. The waveguides have been designed with varying inner radius between 0.75 mm to 0.95 mm to achieve phase velocities close



(a) (b)

Figure 3: (a) Photograph of two 3D-printed steel waveguides. (b) Microscope image of the largest waveguide.

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