Theoretical and Experimental Study of High-Q Resonant Modes in TeraHertz Optical Systems

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Abstract

The existence of multiple reflections in TeraHertz optical system causes numerous problems in applications ranging from astronomical to medical instrumentation. We have performed a detailed theoretical study, using waveguide and free-space modal matching, of the high-Q modes that appear on THz optical paths. Highly accurate measurements at 0.48 THz reproduce in detail the complex behaviour that was predicted theoretically. This work opens up the possibility of designing schemes for removing these troublesome effects.

Introduction

In many THz optical systems performance is in some way affected by the presence of multiple reflections. They can show up for example as baseline ripple in spectrometers, beam profile ripple in antenna measurement systems and structure not related to the sample in imaging systems. Usually these effects are studied empirically or only modeled to first order by assuming a sinusoidal variation with distance and wavelength. In this paper we consider the coupling between two horns in configurations that appear for example in antenna measurement systems and in the Local Oscillator (LO) paths of heterodyne receivers. We present an analytical technique that takes into account the total transmission and reflection properties of the optical components in the system. Whereas standing wave patterns are usually expected to be sinusoidal, we demonstrate theoretically and by experiment that the presence of high-Q resonant modes can result in irregular and non-sinusoidal standing wave structure.

Theory

We have combined the modal matching technique used to analyze waveguide devices[1] with a scattering matrix formulation of free-space Gaussian beam-mode analysis used to describe the quasi-optical system[2]. In this approach the full scattering response of the horn to an arbitrary field is obtained by cascading the waveguide mode scattering matrix of the horn with a scattering matrix that connect the waveguide modes to propagating free-space Gaussian modes. Therefore not only scattering from the aperture but also from inside the horn is taken into account. Scattering matrices for the free-space Gaussian modes are formulated for propagation over a certain distance and the phase transformation by a focusing element[3]. The presence of reflections from actual devices in the horn waveguide is represented by a partially reflecting sheet. The total transmission and reflection properties of the quasi-optical system are finally obtained by cascading the scattering matrices of the subsections of the system. In this way full track is kept of both the forward and backward going components of the propagating fields in the entire system.

Analysis and Measurement Results

The outlined theory has been applied to two specific examples. In the first case we consider the case of two matched horns. In this case the fundamental Gaussian beam mode present in the aperture field of one horn is transformed by an optical system such that it fully matches with the fundamental mode present in the aperture field of the other horn. This case represents for example the LO path in a heterodyne receiver.

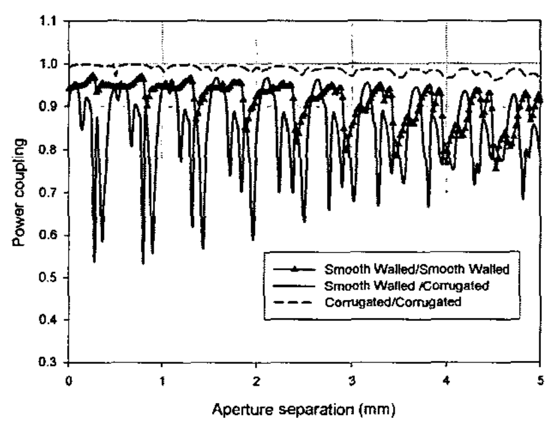

Fig. 1. Comparison of horn to horn coupling calculated using different horn geometries.

In Fig. 1 we show the total transmission from transmitting to receiving horn as function of the defocus of one of the horns. We present the power coupling for three different combinations of horn geometries. The main resonances appear every 0.5 mm as expected for a wavelength of 1 mm used in the simulation. The predicted pattern is however not sinusoidal and reveals multiple pathlength resonances. We attribute this behaviour to the existence of high-Q resonant modes that get trapped in the cavity formed between the two horns. High-order modes of one horn only weakly couple to the other horn and set up a high-Q cavity. This explanation is supported by comparing the results for different horn geometries which clearly illustrate that the resonant behaviour increases for the case of two different horns at both ends. The results shown in Fig. 1. also indicate that horn geometry is important regarding standing wave structure.

In the second example we model the case of two horns without intermediate optics. This case is representative of the situation that occurs in an antenna measurement setup where the beam profile of one horn is scanned by another horn. In Fig. 2 we show the simulated and measured standing wave patterns obtained for two corrugated horns operated at 0.48 THz. The test-setup used for this experiment is described in detail in [4]. We obtain good general agreement between theory and experiment. The measured and predicted coupling falls off at the same rate with increasing aperture separation. Comparison of measured and predicted coupling confirms the existence of high-Q resonant features. In the limit of large aperture separation, and hence higher coupling loss, the standing wave pattern reduces to a sinusoidal modulation with distance. This is again strong evidence that the high-order modes present in the system are responsible for high-Q resonant behaviour since they diffract out of the system for large aperture separation.

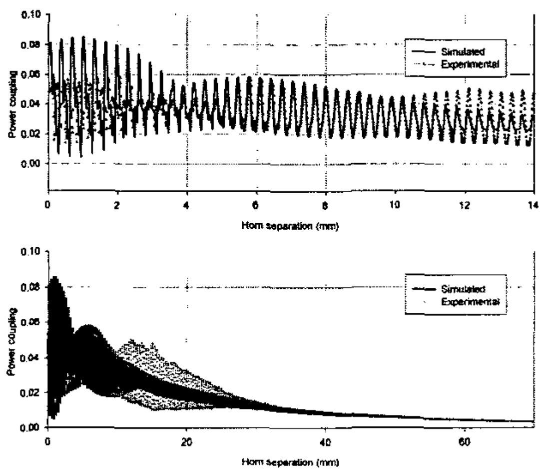

Fig 2. Measured and predicted standing wave pattern for two unmatched corrugated horns.

Summary and Conclusions

In this paper we have presented a technique to predict the coupling between two horns in TeraHertz optical systems taking into account the presence of multiple reflections. The technique is based on combining the waveguide modal matching technique and a scattering matrix formulation of Gaussian beam-mode analysis. We have applied the theory to predict the coupling between two horns with and without intermediate optics as the distance between them is varied. The high-Q resonant features predicted theoretically have been confirmed experimentally. The presence of high-Q resonant modes in TeraHertz optical systems can have important consequences for example pathlength stability in the LO paths of heterodyne receivers, standing wave ripple in antenna measurement systems, electromagnetic interaction between transmitting and receiving waveguide devices, baseline ripple due to modulated system gain in spectrometers and image structure not related to the real sample in imaging systems. This work opens up the possibility to control structure and features caused by multiple reflections and to design schemes that remove these troublesome effects.

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