Development of an electro-optic resonator probe for Terahertz imaging

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Abstract: We introduce the concept of an electro-optic resonator to improve resolution and enhance sensitivity in Terahertz near-field imaging. Different design parameters are considered and discussed. The optimum design in terms of 3dB-bandwidth, reflectivity, and electro-optic enhancement is deduced and presented.

1 Introduction.

Research on systems and devices employing the Terahertz frequency range has gained increasing interest during the last years due to its manifold potential applications ranging from communications [1] and security screening [2] to applications in medicine and biotechnology [3]. Furthermore, the Terahertz range allows the investigation of fundamental physical phenomena since molecular and atomic vibrations as well as surface plasmons can be observed in this energy range. In order to fully exploit the possibility of Terahertz imaging, one has to apply near field techniques to overcome the diffraction limit which restricts the resolution of an optical imaging system (≈1mm in the THz regime).

There are currently three optical near-field imaging techniques commonly used: one is the “aperture approach” with which a resolution of 7μm has been achieved [4]. Thereby, a sub-wavelength aperture is used to spatially select and probe the Terahertz field. Another technique is the tip approach. Hereby, a metallic tip acts as an antenna whose impedance is modulated by the material properties in the near field of the tip. In this case, a resolution of 150nm was reported by [5]. Although either techniques offer a very good resolution, they suffer from two main drawbacks: the use of metallic elements can severely distort the electromagnetic field and both the aperture and the antenna have a frequency selective response. As a consequence, these techniques cannot always be applied when accurate imaging of the electromagnetic field distribution is necessary. In order to tackle this disadvantage, electro-optic sampling can be used as the third near-field imaging approach. This technique exploits the electro-optic effect, in which an electromagnetic field induces birefringence in an electro-optic probe. The Terahertz field is then detected as a change in the polarisation state of a probing beam. The low invasiveness of an electro-optic probe makes it a very promising and advantageous tool to map electromagnetic fields and to observe physical phenomena in the Terahertz range.

In this paper, the development of an electro-optic near-field probe that has been proposed in [6, 7] is presented. The idea of a Fabry-Perot cavity is introduced and its design parameters are discussed. The influence of the symmetry of the cavity, the reflectivity of the mirrors, the spacer thickness, and the pulse width of the probing beam on the performance is shown. Finally, the optical properties of the fabricated microresonator are characterised and compared with the simulation.

2. Microresonator for Terahertz Near-Field Imaging.

Although the electro-optic sampling was introduced as a very powerful technique to detect Terahertz fields, it suffers from a main drawback: the electro-optic effect in commonly used electro-optic materials is very weak. The introduced phase shift Δδ to a probing beam with the wavelength λ due to the applied electric field strength E in a material with the electro-optic coefficient r, the refractive index n and the optical path length l can be calculated by:

$$\Delta\delta = \pi\, r\, n^3\, E\, l / \lambda \qquad (1)$$

The electro-optic coefficient r is normally in the range of 10^{-12} pm/V which makes the phase shift very small and hard to detect. Taking formula (1) into account for a specific electro-optic material, one can only increase the optical path length in order to enhance the electro-optic effect and obtain an improved sensitivity. This leads to the use of large crystals which directly sets restrictions to the achievable resolution. The best reported resolution using electro-optic sampling was 20µm [8] and is not as good as the other near field imaging techniques mentioned before.

The electro-optic probe introduced here takes advantage of the Fabry Perot effect in order to enhance its performance compared to a bulk crystal. As it is schematically shown in Figure 1, a comparably small Fabry-Perot resonator can replace a much bigger bulk crystal without reducing the optical path length of the probing beam in the electro-optic probe.

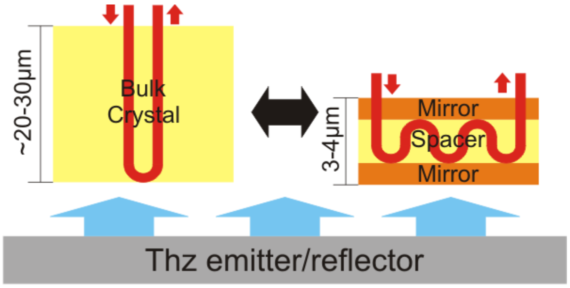

Figure 1: Schematic comparison of the optical pathlength in a bulk crystal and a Fabry-Perot Cavity

Since the electro-optic effect in the microresonator is comparable to the one in a bulk crystal, this cavity offers an exceptional sensitivity with respect to its size. The small dimensions of the probe additionally provide a high degree of non-invasiveness and an improved resolution. The frequency response can be assumed to be very flat since no frequency selective features are involved. The only limiting factor to its bandwidth is the total duration of stay of the probing optical pulse in the cavity which should not exceed half of a period of the Terahertz wave. Furthermore, the design of this probe allows attachment to an optical fibre. A fibre coupled electro-optic probe would be very beneficial for Terahertz imaging since it allows free positioning of the probe with respect to the sample.

3. Design Considerations

The mirrors of the Fabry-Perot cavity are designed as Distributed Feedback Reflectors (DBR) and use consecutive λ/4 - layers of GaAs and $Al_{90}Ga_{10}As$. The difference in their refractive indices is relatively big ($n_{GaAs} \approx 3.5$, $n_{AlGaAs} \approx 3$) which makes the stop band of the Fabry Perot cavity large. The spacer is made of GaAs since it offers a higher refractive index which directly increases the electro-optic effect according to formula (1).

In order to simulate the optical performance of the Fabry Perot cavity, a program has been written which employs the Optical Admittance Approach described by MacLeod [9] and a model of the refractive index that is presented by Aframowitz [10].

As a first approach, we aimed to design an electro-optic probe with a 3dB – bandwidth that exceeds 1.5 THz and an overall reflectivity of more than 90%. A high reflectivity is important to minimise the exposure of the sample to the beam. Additionally, the electro-optic enhancement should be as high as possible and the thickness as small as possible. In order to achieve this performance, one can alter the reflectivity of the mirrors, the thickness of the spacer layer and the symmetry of the design. As a further point, it is important to investigate the influence of the pulse width of the probing beam on the performance of the microresonator.

With respect to the symmetry of the design, one has to discard the idea of using a symmetric resonator. A symmetric design causes a long duration of stay of the probing beam in the cavity which indeed causes a strong electro-optic effect but also significantly decreases the bandwidth. A Fabry-Perot resonator in that case is almost transparent at its resonant wavelength and the measurement of the phase shift in the reflection mode is hardly possible. Due to that, an asymmetric microcavity is clearly preferable. Regarding an asymmetric resonator, one has to determine the position of the low- and high-reflectivity DBR with respect to the sample and the probing beam respectively. Positioning the thinner low-reflectivity DBR on the spacer side which is facing the sample moves the resonator closer to the sample and improves the lateral resolution. However, the high-reflectivity DBR as the top mirror instantly reflects almost the entire incident probing beam before it is able to enter the resonator and minimises the electro–optic effect. As a consequence, the thicker high-reflectivity DBR has to be positioned at the spacer side facing the sample.

A further point is the reflectivity of the two DBRs which is directly determined by the number of λ/4 – GaAs/$Al_{90}Ga_{10}As$ layers. Simulations show that a higher number of DBR layers form a much narrower and deeper resonance. By significantly increasing the number of λ/4 - layers in both DBRs one approaches the behaviour of a high Finesse Fabry-Perot cavity. As already mentioned above, this enhances the electro-optic effect but significantly decreases the bandwidth. With respect to the desired performance and taking into account the results of the simulations, a configuration with 5 λ/4 - layers in the low-reflectivity DBR and 15 λ/4 - layers in the high-reflectivity DBR has been chosen.

As another degree of freedom, the thickness of the spacer can be varied. Following the requirements of a Fabry Perot cavity, the thickness has to be a multiple of λ/2 - layers. The influence of the varying thickness of the spacer on the 3dB - bandwidth, the electro – optic enhancement and the reflectivity is shown in Figure 2(a). We defined the term "electro-optic enhancement" as the increase in the phase shift due to the resonant cavity in comparison to a bulk crystal of the same length. In the simulation, a configuration with DBR thicknesses of 5 and 15 λ/4 - layers and a pulse width of 120fs have been used. One can clearly see that a spacer thickness of 3 or 4 λ/2 - layers show the best performance. Since the thickness of the whole structure should be as small as possible, the first option has been chosen.

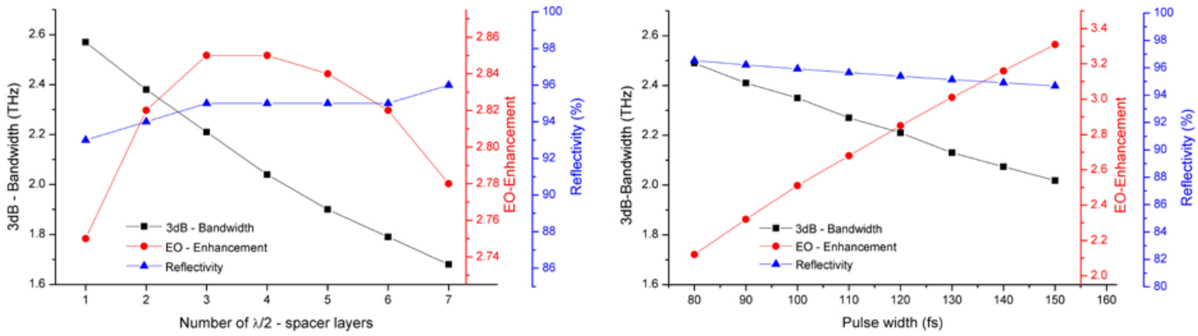

Figure 2: The 3dB - bandwidth, the electro-optic enhancement and the reflectivity of the microresonator as a function of a) the number of spacer layers and b) the pulse width

The influence of the pulse width of the probing beam on the performance of the microresonator is investigated and shown in Figure 2(b). It is important to know that the pulse width has a high impact on the behaviour of the resonator. This parameter must be taken into account as a further degree of freedom when carrying out simulations to determine the final structure of the resonator or taking measurements in order to characterise its performance.

4. Experimental results.

Considering the results of our simulations, we chose a final design of the microcavity with 5 λ/4 DBR - layers in the top mirror and 15 λ/4 DBR - layers in the bottom one. The thickness of the spacer comprises 3 λ/2 – layers of GaAs. The structure was designed for a wavelength λ of 980nm which entails a total thickness of the microcavity of approximately 3.5µm.

A microresonator with these dimensions has been fabricated by Molecular Beam Epitaxy. Its reflectivity has been measured and compared to the simulated curve in Figure 3. The measured curve fits the simulated one very nicely, confirming the accuracy of the used model.

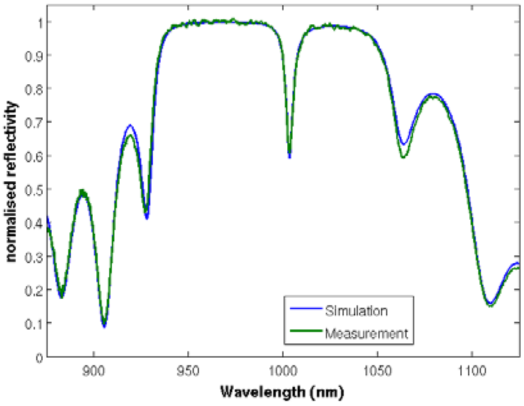

Figure 3: The measured and simulated normalised reflectivity of the microresonator

5. Summary.

The idea of an electro-optical microresonator as a probe for Terahertz near-field imaging has been introduced and compared to other current Terahertz near-field techniques. Different design parameters have been considered and discussed. The final design has been chosen to have 5 λ/4 – DBR layers in the top mirror and 15 λ/4 - DBR layers in the bottom one. The spacer has a total thickness of 3 λ/2 – layers. It has also been shown that the pulse width of the probing beam severely influences the resonator performance. Finally, the microresonator has been fabricated and its reflectivity characterised.

Experimental work is currently conducted to test the fabricated cavity for detection of Terahertz waves and to characterise its overall performance.

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