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Interrogating Fabry-Perot ultrasound sensors with Bessel beams for photoacoustic imaging

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Abstract. Photoacoustic Tomography (PAT) systems based on Fabry-Perot (FP) sensors provide high-resolution images limited by the system's sensitivity. The sensitivity is limited by the optical Q-factor of the FP cavity (i.e., the optical confinement of the interrogation laser beam in the FP cavity). In existing systems, a focussed Gaussian beam is used to interrogate the sensor. While providing a small acoustic element required for high-resolution imaging, this interrogation beam naturally diverges inside the FP cavity, leading to the current sensitivity limit. To break this limit, a new approach of interrogating the FP sensor using a Bessel beam is investigated. The Noise Equivalent Pressure (NEP) and both axial and lateral PAT resolutions using Bessel beam interrogation were quantified. Bessel beam interrogation provided lower NEP, similar axial resolution, but lower lateral resolution. Thus, Bessel beam might be an alternative interrogation scheme for deep PAT imaging as high sensitivity is needed and the lateral resolution is limited by the aperture of the PAT system.

1 Introduction

Planar Fabry-Perot (FP) sensors are widely used for Photoacoustic Tomography (PAT). Their combination of broad ultrasonic bandwidths, small acoustic element sizes, and high sensitivities allow the acquisition of PAT images with high spatial resolution ($< 100\,\mu\mathrm{m}$). While the penetration depth is limited to about $15\,\mathrm{mm}$, this might be significantly extended by increasing the FP sensor sensitivity.

An FP sensor is an interferometer comprising an optical cavity formed between two parallel mirrors. The FP sensor is illuminated with a laser beam to be interrogated. The sensitivity is proportional to the maximum absolute derivative of the Interferometer Transfer Function (ITF), namely the reflected optical power as a function of the wavelength. The sensitivity relates to how well the FP cavity confines the interrogation beam as it reflects back and forth between the mirrors.

To confine the beam over a long optical path for high sensitivity, FP sensors are typically designed with high mirror reflectivities. In principle, the sensitivity can be further extended by increasing the reflectivity. However, in existing systems, the sensitivity is capped for reasons related to the structure of the beam. Briefly, to obtain strong beam confinement requires the beam to not diverge inside the cavity. However, in planar FP sensor, a focused Gaussian beam, required for the small acoustic element size, naturally diverges due to the short depth of focus of focused Gaussian beam. For this reason, ITFs, using focused Gaussian beam interrogation, have reduced contrast and sensitivity when the mirror reflectivities are increased [1]. This challenge can be addressed by changing the shape of the FP cavity to refocus the Gaussian beam in a round-trip basis, as in Plano-Concave Microresonator (PCMR) [2]. While enabling order of magnitude sensitivity increases, there are new challenges associated with the fabrication and interrogation of PCMR, as opposed to planar sensors.

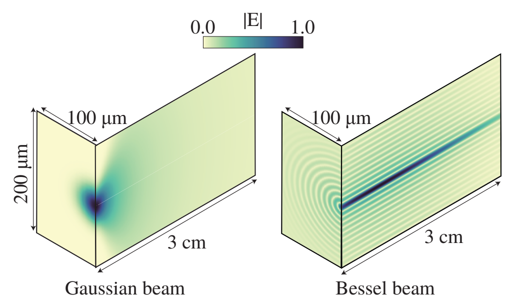

Figure 1: Electric field amplitude of Gaussian and Bessel beams.

As an alternative approach to improve the beam confinement inside the cavity, in this work, the use of a Bessel beam as the interrogation beam for planar FP sensors is examined. Bessel beams have extended depth

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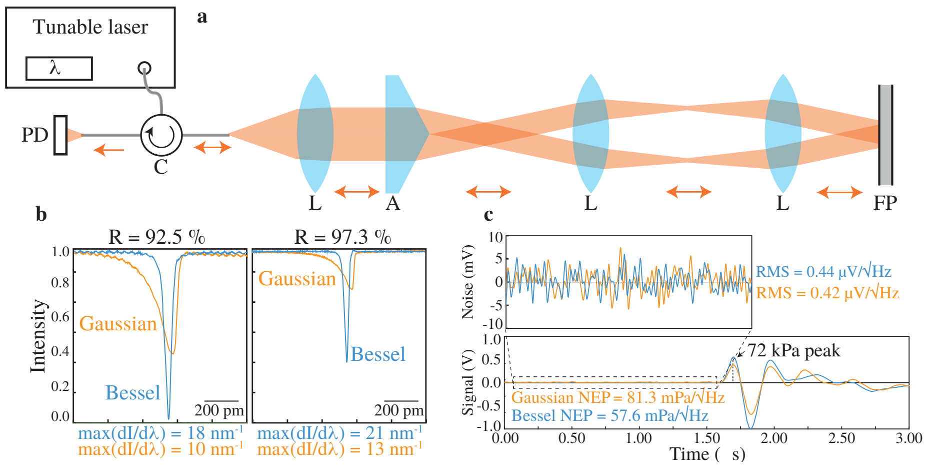

Figure 2: a) Diagram of the system used for Bessel beam interrogation. Abbreviations: circulator (C), lens (L), axicon (A) and FP sensor (FP). b) ITFs acquired with Gaussian and Bessel interrogation. c) Response of the FP sensor to an incident 72 kPa ultrasonic plane wave using Gaussian and Bessel interrogation.

of focus which should lead to increase the sensitivity of the FP sensor [3]. Moreover, like a Gaussian beam, Bessel beams can also be focused to provide a microscale spot, as exemplified in figure 1, providing a small acoustic element. However, contrary to Gaussian beams, Bessel beams have side lobes around the microscale core which could increase impact the acoustic element size. Thus, to investigate the feasibility of Bessel beam interrogation, a system to acquire PAT images using Bessel beam interrogation was prototyped. The Noise Equivalent Pressure (NEP), axial and lateral resolutions of the system were quantified.

2 System

The FP-based PAT system prototyped is illustrated in figure 2a. Light from a CW tunable laser was delivered by a single-mode fibre and collimated by a lens. The collimated beam illuminated the back of the axicon to generate a Bessel beam with a $5\,\mathrm{cm}$ depth of focus and a $30\,\mu\mathrm{m}$ core. The Bessel beam was relayed by telescope with magnification of 1 to illuminate the FP sensor. The FP sensor used had a $300\,\mu\mathrm{m}$ thick fused silica cavity. Also, both FP mirrors had variable reflectivity from $92\,\%$ to $98\,\%$ within the wavelength range of the tunable laser. Light reflected by the FP sensor propagated back through the system and was redirected to an InGaAs photodiode using a fibre circulator. The signal from the photodiode was amplified by a custom made transimpedance amplifier and readout by an oscilloscope.

3 Results

To test if using the Bessel beam provides higher sensitivity, ITFs were measured and compared to those measured with a Gaussian beam with waist of $50\,\mu\mathrm{m}$. Both beams' core sizes were similar but the ITFs measured with each beams differ considerably, as shown in figure 2b. In particular, the ITF measured assuming Gaussian beam interrogation has low contrast and high Full Width at Half Maximum (FWHM). In comparison, when using Bessel beam interrogation, the ITF has a higher contrast and lower FWHM. For this specific FP sensor changing the interrogation beam led to an increase in the ITF sensitivity by 1.8 times. To confirm if the gain in sensitivity led to a reduction in the NEP, the NEP was quantified by measuring the response of the sensor to a calibrated ultrasound transducer. The NEP measured using Gaussian and Bessel interrogation was $81.3\,\mathrm{mPa}/\sqrt{\mathrm{Hz}}$ and $57.6\,\mathrm{mPa}/\sqrt{\mathrm{Hz}}$, respectively, confirming that the gain in sensitivity led to a reduction in the NEP.

The core of the Bessel beam considered was smaller than the Gaussian beam waist. However, a considerable part of the Bessel beam energy was on the side lobes of the Bessel beam, as shown in figure 1. The side lobes of the Bessel beam might impact the acoustic element size which impacts the lateral resolution of the PAT system. To study the acoustic element size using Bessel beam interrogation, photoacoustic tomography images were acquired using both interrogation schemes to quantify the lateral resolution. The images were acquired by translating a phantom made with hairs along the fixed interrogation point on the FP sensor, as illustrated in figure 3a.

The images were reconstructed using k-wave [4]. To quantify the lateral resolution, a cross section along the x-axis across a hair was taken and fitted to a Gaus-

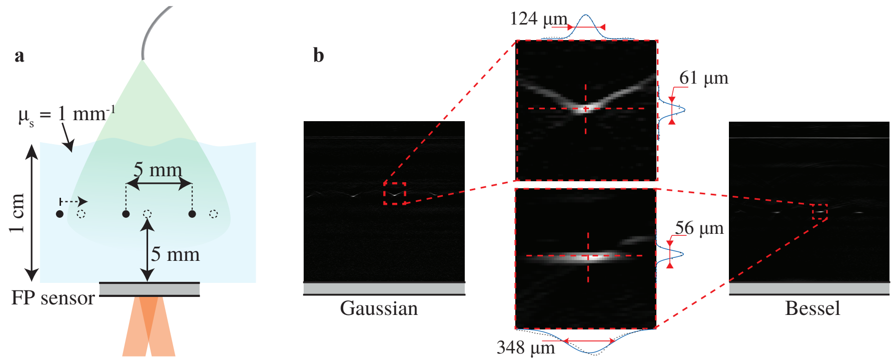

Figure 3: PAT images using Gaussian and Bessel interrogation. a) Phantom schematic. The phantom was translate 1 cm along the FP sensor. b) Cross section of the hairs to quantify the resolution of both systems.

sian profile. For Gaussian and Bessel interrogation, the FWHM of the Gaussian profile were 124 µm and 348 µm, respectively. Using the same approach, the axial resolutions was measured to be 61 µm and 56 µm, for Gaussian and Bessel beam interrogation, respectively.

In photoacoustic tomography, the axial resolution depends on the frequency response for ultrasound waves at normal incidence, which is independent on the interrogation beam. However, the lateral resolution relates to the directivity dependent frequency response of the sensor, which depends on the acoustic element size. Thus, the lateral and axial resolutions suggests that the acoustic element size of the Bessel beam used is considerably bigger than the Gaussian beam creating a more directional sensor. To confirm this hypothesis, the directivity dependent frequency response of the sensor was measured using both interrogation beams. The measurement, plotted in figure 4, was performed by measuring the sensor response as a broadband laser-generated ultrasound source is rotated relatively to the interrogation point.

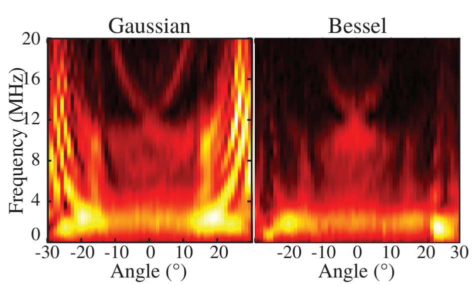

Figure 4: Directivity dependent frequency response using Gaussian and Bessel beam interrogation.

At normal incidence, the measured frequency response using both interrogation schemes were similar as expected because the frequency response at normal incidence is only dependent on the FP cavity material and thickness. However, as the ultrasound angle of incidence increases, both interrogation schemes had different directivity dependent frequency response. Gaussian interrogation had a wider directional response relatively to Bessel interrogation, as visible in figure 4. Thus, the acoustic element size provided by the Bessel beam limited the directional response of the FP sensor reducing the photoacoustic image lateral resolution.

Bessel interrogation provided higher sensitivity but reduced lateral resolution relatively to Gaussian interrogation. Thus, a trade-of between resolution and sensitivity exists when considering Bessel beam to interrogate FP sensors.

4 Conclusion

A prototype of FP-based PAT system employing a Bessel interrogation beam was developed. The extended depth of focus of the Bessel beam reduced the beam walk-off inside the FP cavity reducing the NEP of the FP sensor. However, light present on the Bessel side lobes increased the acoustic element size leading to an reduction in the lateral resolution of the PAT image. Bessel beam provide an alternative interrogation scheme particularly interesting for deep tissue imaging where high sensitivity is needed and the image resolution is limited by other factors (ultrasound aperture and tissue absortion of the high ultrasound frequency components).

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