Note on Far-field Pattern Measurement Setup

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Introduction

Collimated and narrow laser beams are ideal for many industrial applications, including free-space communication, light detection and ranging (LiDAR), and material processing. Practical laser beams, however, are not perfectly collimated and always bear finite divergence angles. That is to say, the diameter of the laser beam changes along its propagation direction. Far-field pattern measurement serves to quantitatively characterize such imperfections of laser beams. In such measurement, the light emission intensity of a laser is measured for each individual emission direction, and an angular power spectrum, or far-field pattern, is obtained. This far-field pattern allows us to evaluate the quality of the laser beam. In this note, I will introduce the design of a measurement setup for characterizing the far-field patterns of lasers. This setup is designed for measurements within the near-infrared wavelength range, typically around 1300 nm or 1550 nm.

Overview of Measurement Setup

Figure 1 shows our measurement setup for characterizing the free-space beam of a laser. This setup allows us to measure the power, optical spectrum, and far-field pattern of the laser beam. The laser under test is driven by a current source and emits a free-space optical beam. This laser beam is collimated by an objective and then gets divided into two beams by a non-polarizing beamsplitter. The first beam enters a beam expander, where its diameter is adjusted to match that of an infrared sensor. This sensor images the optical intensity profile of the laser beam, which can be used to reconstruct the far-field pattern of the laser. The second beam is split into another two beams by a second non-polarizing beamsplitter. The resulting two beams are characterized by a photodetector and an optical spectrum analyzer, respectively, allowing us to measure the total power and optical spectrum of the laser beam.

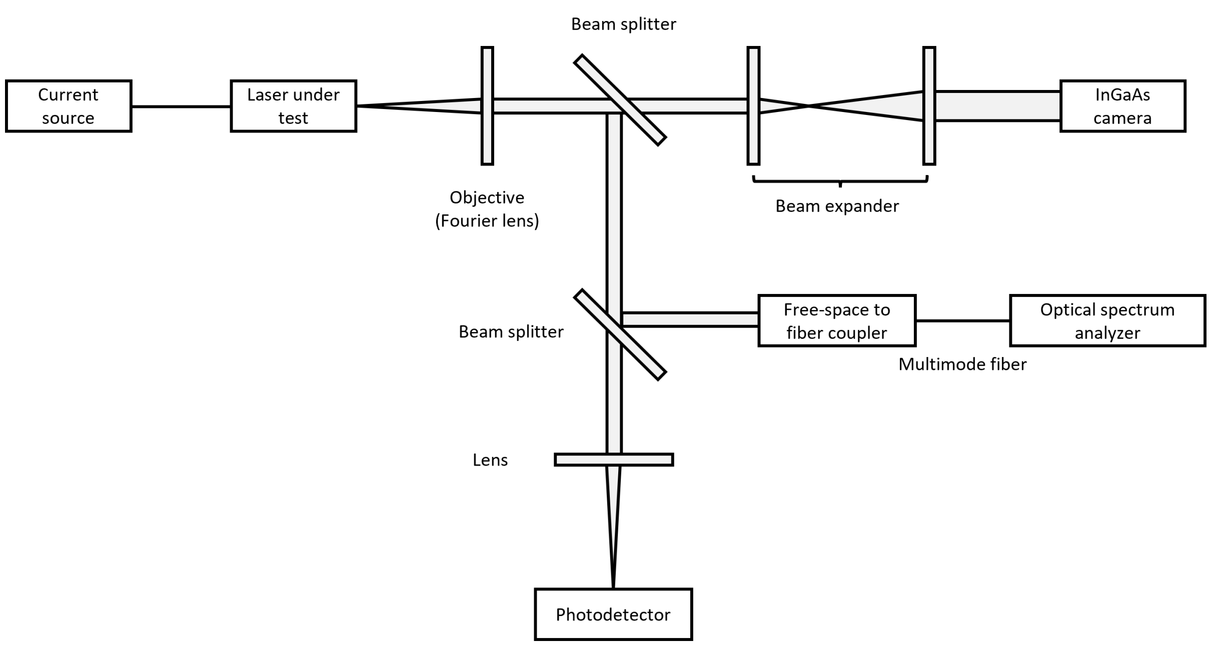

Figure 1: Schematic of far-field pattern measurement setup source.

Specifications and Cost of Measurement Setup

- Field of view: 50° in both x and y directions
- Working distance: 17 mm (gap between sample and objective)
- Angular resolution: 0.05°

Key Modules

This measurement setup comprises several key modules that need a bit more consideration for their complicated design or relatively high prices. These modules include (1) objective, (2) beam expander and infrared camera, and (3) free-space to fiber coupler. In this section, we introduce the design and specifications of these modules in detail, which hopefully will become a useful guide for readers who want to build their own laser beam characterization platforms.

Objective

The first step of our measurement is to collimate the optical beam emitted by the laser under test. This can be done by using a long working distance objective. The laser output facet is placed on the front focal plane and optical axis of the objective, leading to parallel optical output from the objective, which makes it convenient to conduct subsequent measurements.

Regarding the model selection of the objective, there are three key parameters to be considered: numerical aperture (NA), effective focal length, and working distance (WD). We will use a specific model of objective, Mitutoyo M Plan Apo NIR 50X, to explain how these specifications affect the overall performance of our far-field pattern measurement setup. The specifications of this objective are shown in Figure 2. This objective has an NA of 0.42, indicating that it can collect and collimate light with an incident angle no greater than $\sin^{-1}(\mathrm{NA}) = 25°$. This means our measurement setup has a field of view of 50°; it can only characterize far-field patterns within an angular range of ±25°. The Mitutoyo objective has a magnification of 50X, which translates to an effective focal length of $f_{\mathrm{obj}} = 200/50 = 4$ mm (assuming the focal length of the tube lens to be 200 mm). The effective focal length (defined as the distance between the focal plane and principal plane [1,2]) of the objective determines the diameter of the collimated beam. For a laser beam emitted with a $1/e^2$ divergence angle of 2θ, the corresponding $1/e^2$ diameter of the collimated beam is $2f_{\mathrm{obj}}\tan\theta$ [3] (note that we have ignored the impact of a finite field of view). The maximum diameter of the collimated beam, known as entrance pupil diameter (EP), is $\mathrm{EP} = 2f_{\mathrm{obj}}\tan\theta_{\mathrm{max}} \approx 2f_{\mathrm{obj}}\mathrm{NA} = 3.36$ mm. Moreover, the objective has a WD of 17 mm, which means its working plane (a plane perpendicular to the optical axis where the sample should be placed for best imaging quality, equivalent to the front focal plane for an infinity-corrected objective [4]) is at a distance of 17 mm from the physical front end of the objective. Since the Mitutoyo objective is infinity-corrected, we should place the laser's output facet exactly on the working plane of the objective so as to obtain a collimated beam from the objective's rear end.

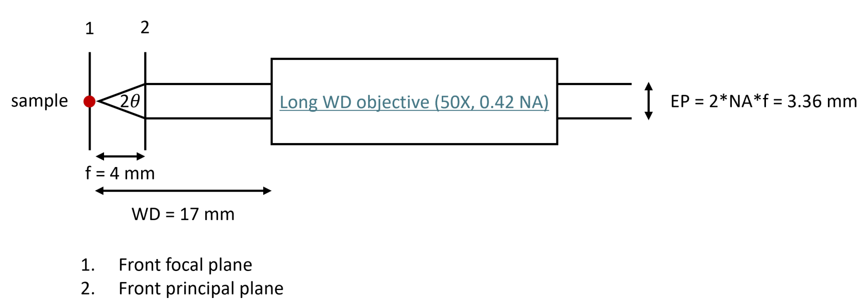

Figure 2: Schematic of objective source.

Model of equipment - Long working distance objective: Mitutoyo M Plan Apo NIR 50X (infinity-corrected, 50X, NA 0.42, WD 17 mm, 3D model)

Beam expander and infrared camera

Our objective is to measure the optical intensity of the laser beam as a function of emission angle. Note that the objective maps the tilting angle of a light ray with respect to the optical axis to the distance of a parallel light ray from the optical axis. Therefore, we only need to measure the optical intensity profile of the objective's output beam, namely its optical intensity distribution over a cross section. To this end, we employ an infrared camera (also referred to as a laser beam profiler) along with a beam expander, both placed behind the objective, as shown in Figure 3.

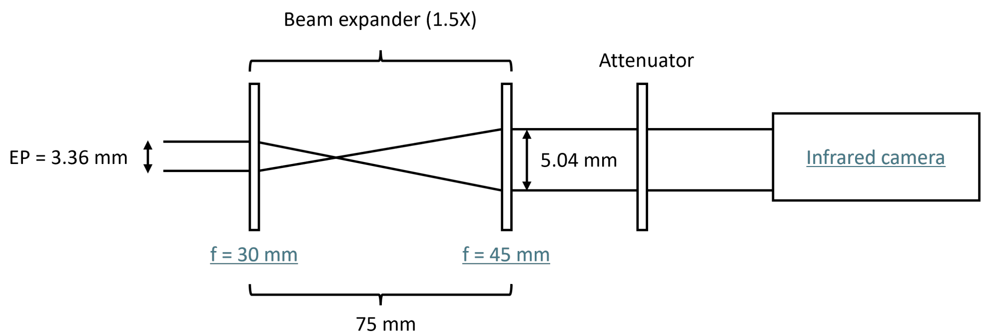

Figure 3: Schematic of beam expander source.

To obtain the maximum resolution of the far-field pattern, the dimensions of the collimated beam should match the size of the infrared sensor. We insert a beam expander between the objective and the infrared camera to achieve this. This beam expander comprises two lenses of different focal lengths. The ratio of the focal length of the rear lens to that of the front lens equals the beam expansion ratio. In our design of the beam expander, the beam expansion ratio is 1.5X, meaning that an entrance collimated beam with a diameter of 3.36 mm will be transformed to one with a diameter of 5.04 mm, which is a good fit for our infrared camera (model: Hamamatsu C16741-40U) with an active area of 6.4 mm x 5.12 mm. Given a pixel size of 5 um x 5 um, the corresponding angular resolution of our far-field pattern measurement setup becomes $\Delta\theta = \text{pixel width}/\text{expansion ratio}/f_{\text{obj}} = 5\ \text{um}/1.5/4\ \text{mm} = 0.05°$.

Models of equipment - Lens: Thorlabas LSB08-C (achromatic) - Infrared camera: Hamamatsu C16741-40U (1280(H) x 1024(V) pixels, pixel size 5 um x 5 um, sensor size 6.4 mmx5.12 mm, 3D model)

Free-space to fiber coupler

Our setup employs a free-space to fiber coupler (model: Thorlabs TC18FC-1310) to couple a laser beam into a multimode fiber, as shown in Figure 4. The multimode fiber is connected to our optical spectrum analyzer (model: Yokogawa AQ6370E) for spectral measurement. The free-space to fiber coupler we use is a fiber-optic collimator. This device functions as a convex lens that focuses the incident collimated laser beam onto a facet of the multimode fiber and thereby couples light into it. Note that the incident collimated laser beam has a diameter no greater than the EP of the objective (=3.36 mm). Moreover, the fiber-optic collimator has a long focal length of 18 mm, meaning that the single-sided divergence angle of the focused laser beam is upper bounded by $\theta = \text{EP}/f_{\text{collimator}}/2 = 0.093$. This value is lower than the NA of our multimode fiber (model: Thorlabs M42L01, NA = 0.22), ensuring a high coupling efficiency from the incident laser beam to the fiber.

Models of equipment: - Fiber optic collimator: Thorlabs TC18FC-1310 (focal length 18 mm, NA 0.28, operating wavelength 1236-1400 nm, 3D model) - Multimode fiber: Thorlabs M42L01 (core diameter 50 um, NA 0.22, 3D model)

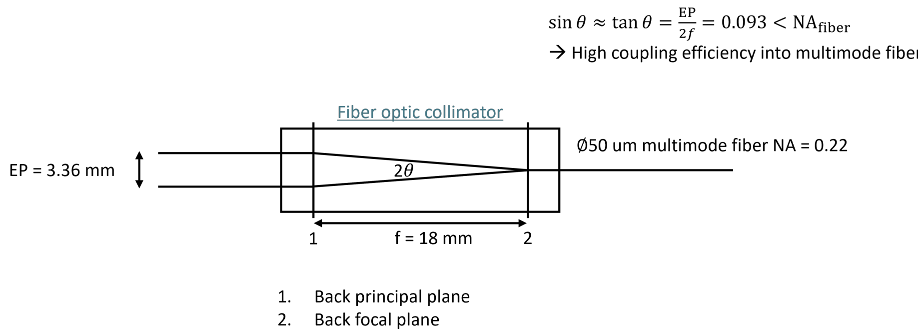

Figure 4: Schematic of free-space to fiber coupler source.

Useful Documents

- Full list of required equipment and reference price
- 3D model (.step) of the measurement setup.

Reference

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1. Greivenkamp, J. E. (2004, January). Field guide to geometrical optics. Bellingham: SPIE.
2. https://en.wikipedia.org/wiki/Focal_length
3. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=9922
4. https://www.olympus-ims.com/en/microscope/terms/feature15/