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Silicon wedge-trap detector for optical fibre power measurements*

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Abstract. We have designed and built an optical fibre power detector based on a large-area silicon PIN photodiode and a concave mirror in a wedge-trap configuration. The detector was designed as a high-accuracy transfer standard for near IR (835–865 nm) optical fibre power measurements with multimode fibre-ribbon cables in a manufacturing-production environment. Additional requirements were that the detector be insensitive to the input beam geometry, and able to accommodate different optical fibre connector types, collimated laser light, and highly diverging light from optical fibres. Four identical copies of the detector were evaluated at the NIST Laser Sources and Detectors Group calibration facility and one was tested in the manufacturing environment. The spatial and angular responsivity was highly uniform and varied less than 1% for angles of incidence ranging from 0° to ±15°. Absolute spectral responsivity measurements, for collimated and diverging light input wavelengths ranging from 672–852 nm, showed quantum efficiencies as high as 99%. Linearity measurements from a few nanowatts to a few milliwatts indicated a nonlinearity of only 0.05%.

Keywords: optical fibre power measurement, absolute spectral responsivity calibration, optical fibre array, field of view measurement, wedge-trap optical detector

1. Introduction

The silicon wedge-trap detector (SWTD) was built in response to a request to transfer a NIST calibration to a detector capable of measuring optical power, over the wavelength range 835–865 nm, emitted from a fibre-ribbon cable. The fibre array consisted of 10 optical fibres spaced at 250 μm intervals with an output beam divergence angle of 30°. This request is challenging because of the large divergence angle presented by the fibre-array output.

When we evaluate an optical fibre powermeter for its suitability for use as a transfer standard, we normally use three different measurement systems, each having a different input-beam geometry as shown in figure 1. The first system measures the meter's absolute responsivity by direct substitution with an electrically calibrated pyroelectric radiometer (ECPR) at several discrete collimated laser wavelengths. The second system measures the meter's absolute spectral responsivity over the entire wavelength range of interest referenced to a pyroelectric wedge-trap detector using an incandescent lamp source and a monochromator [1]. In this case the beam from the monochromator is focused at or just behind the detector surface. The third system is similar to the

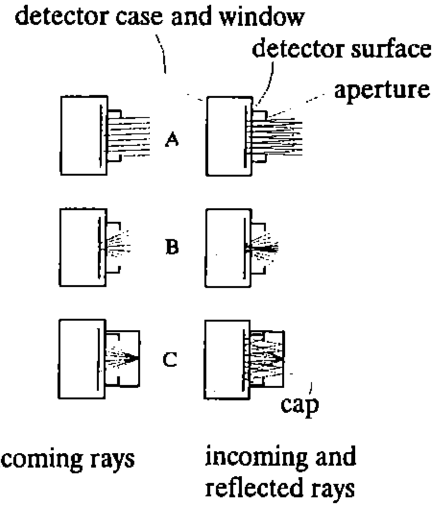

Figure 1. Typical optical fibre power meter input. (*a*) Collimated, (*b*) converging, (*c*) diverging from fibre connector.

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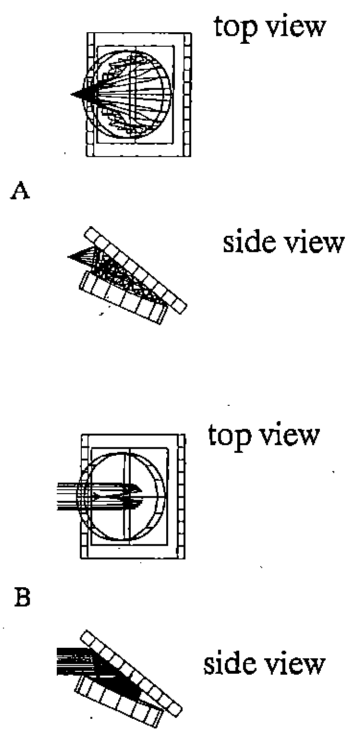

Figure 3. SWTD cross section and ray tracing for (*a*) numerical aperture 0.37 diverging input, (*b*) collimated input.

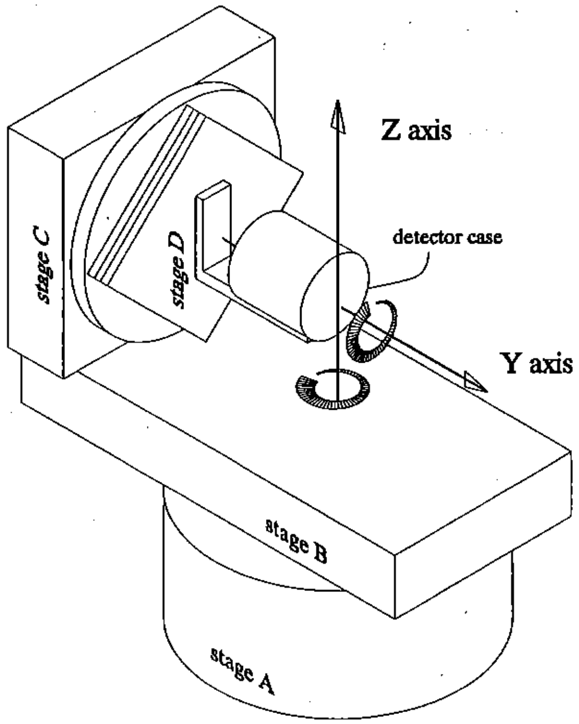

Figure 4. Field of view measurement positioning system.

centre of the aperture into the trap cavity. The image of this concept is similar to that represented by individual rays in figure 3(*a*).

We used a 1 mm diameter, nearly collimated, circularly polarized, 674 nm laser beam as a probe for the measurement. Initially, the detector was mounted so that the aperture was normal to the probe beam ($\theta = 0°$) with the aperture centre located on the optical axis of the probe beam. In addition, the detector was positioned so that the stage-A rotation and stage-C rotation axes intersect at the centre of its aperture. After initial alignment, the detector (stage C) was rotated 360° in 10° increments about the Y-axis, and the detector response was measured at each increment and to acquire one data set. Then, stage A was rotated 10° about the Z-axis, so that the input probe beam entered the detector aperture at θ equal to 10°, and the 360° measurement scan was repeated. A similar process was repeated for θ equal to 15°. All of the data were normalized to the responsivity at 0° and normal incidence. The results, as shown in figure 5, show that the detector responsivity varies less than 1% up to 15°. This measurement technique was useful for confirming the predictions of ray tracing and subsequently refining our design.

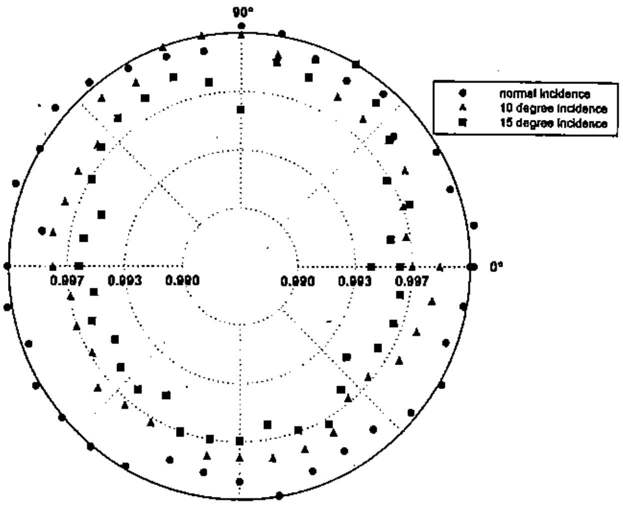

Figure 5. Three data sets depict the detector relative responsivity (log-scale radius) as a function of position. The detector is rotated 360° about the optical axis intersecting the centre of the detector aperture for three incidence angles.

4. Spectral responsivity

We have measured the absolute spectral responsivity of all four of the detectors we have built thus far and are able to make several observations. The overall quantum efficiency is quite high, especially over the wavelength range from 600 to 900 nm. For example, the average absolute responsivity for all four detectors at 852.1 nm was 0.68 A W^{-1}, which corresponds to a quantum efficiency of 99% [6]. At wavelengths shorter than 600 nm, the overall trap-absorption efficiency decreases, as we would expect because the reflectance of silicon increases below 600 nm. Since this detector is used as a transfer standard, and is calibrated against higher accuracy primary standards, the internal quantum efficiency of the photodiode is not critical. However, the internal quantum efficiency of the selected photodiodes is very close to unity and may contribute to the overall spatial and angular uniformity of the detector, which is critical for a high-accuracy transfer standard for optical fibre power measurements [7].

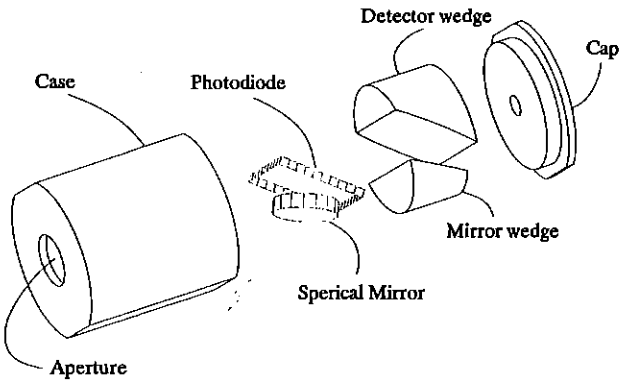

Figure 2. Exploded view of the SWTD assembly and components.

first except that the laser light is coupled to the meter and the ECPR using a fibre-optic cable and connector, and the beam is diverging from a point somewhere in front of the detector. Comparison of the measurements with the first and third system reveals possible offsets that may result from the use of a particular fibre connector and provides a basis for comparison of absolute spectral responsivity data with and without optical fibre connectors.

Typically, light from the fibre has a divergence angle that is less than 14° (±7° from normal incidence). In most cases the fibre connector completely encloses the input aperture of the detector and allows only light transmitted through the fibre to illuminate the detector; light reflected from the detector or detector window may be reflected between the fibre connector and the detector package. The ideal detector would have the same absolute responsivity for any of these beam geometries [2].

Most high-accuracy optical-powermeter detectors (such as trap detectors) are well suited only for nearly collimated or slowly diverging light input conditions. One such device incorporates three photodiodes (each diode, 10 mm× 10 mm) in a five-bounce trap configuration [3, 4]. However, this design is poorly suited for measuring the optical power emerging from the end of an optical fibre because the beam gradually expands to an area that is too large for the most distant detector elements. A photodiode attached to an integrating sphere with an open input port is less preferred for measurements involving optical fibre connectors because different connectors can change the sphere-detector responsivity, which may result in inconsistent calibration offsets. An integrating sphere also results in optical signal attenuation (20–30 dB) which may increase the measurement uncertainty for measurements that involve low-power sources.

Thermal detectors with black absorbing surfaces have demonstrated consistent calibration results for collimated-beam, diverging-beam, and fibre-connector (diverging-beam) measurements. For example, our ECPR reference has a gold black coating which covers a large detector area and results in an insignificant, diffuse reflection in the visible and near IR wavelength range [5]. However, thermal detectors that have long time constants and require modulated inputs are neither suitable for use in production environments nor convenient for fibre-coupled input.

The silicon wedge-trap detector is capable of accurately and consistently measuring optical power from a variety of sources including widely diverging as well as collimated sources. A description of the detector design follows along with measurement results that indicate that the detector is well suited as a convenient transfer standard for optical fibre power measurements.

2. Trap design

A perspective view of the detector assembly is shown in figure 2. The trap geometry has a numerical aperture of 0.37 and an aperture area that is 10 mm in diameter. Light entering the trap (normal to the aperture plane) intersects a 28 mm × 28 mm PIN silicon photodiode at a 52° angle of incidence[†]. A concave mirror faces the photodiode at a 15° angle and repeatedly reflects radiation not absorbed by the photodiode back onto the photodiode surface. Photons entering the trap have at least four chances to be absorbed by the photodiode.

The basic wedge-trap design is not new, and has been used in our measurements with the pyroelectric detector element mentioned above [1, 3]. The present design is similar except that a concave silver-coated mirror rather than a flat gold-coated mirror is used. The mirror, having a 25 mm diameter and a 100 mm radius of curvature, was determined by iterative ray-tracing analysis to be useful for sources with an angle of divergence up to 40°.

Figure 3 shows two ray-traces, ranging from highly diverging to collimated beams, superimposed on a cross-sectional view of the trap cavity. Figure 3(*a*) depicts a pattern for rays diverging 40° (worst case for 0.37 numerical aperture). In figure 3(*b*), a pattern representing rays from a 5 mm diameter, collimated light input is shown.

3. Field of view

We measured the detector responsivity as a function of angle of incidence θ for two reasons: first, to determine the extent to which the detector may be tilted relative to the input beam without affecting the detector responsivity, and second, to determine the extent to which the detector will accurately measure diverging optical input, such as that from the end of an optical fibre.

We measured the responsivity as a function of θ using an apparatus consisting of a manually rotated platform stage (stage A), a manually translated linear stage (stage B), a motorized rotary stage (stage C) and a two-axis levelling platform (stage D) as shown in figure 4. After alignment, the detector, stage C, and stage D are effectively a rigid body and rotate about the Y-axis. Rotation of the entire ensemble about the Z-axis determines the value of θ. The probe beam revolves relative to the detector through 360° at 10° increments for each θ. From this perspective, the measurement approximates a beam diverging $\pm\theta$ from the

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[†] The manufacturer specification (Hamamatsu part number S3584-05) for the 28 mm × 28 mm photodiode used is 500 μm thick, PIN silicon having greater than 75% internal quantum efficiency for the wavelength range 600–1000 nm. The use of tradenames does not constitute an endorsement by NIST and is given here only for reference.

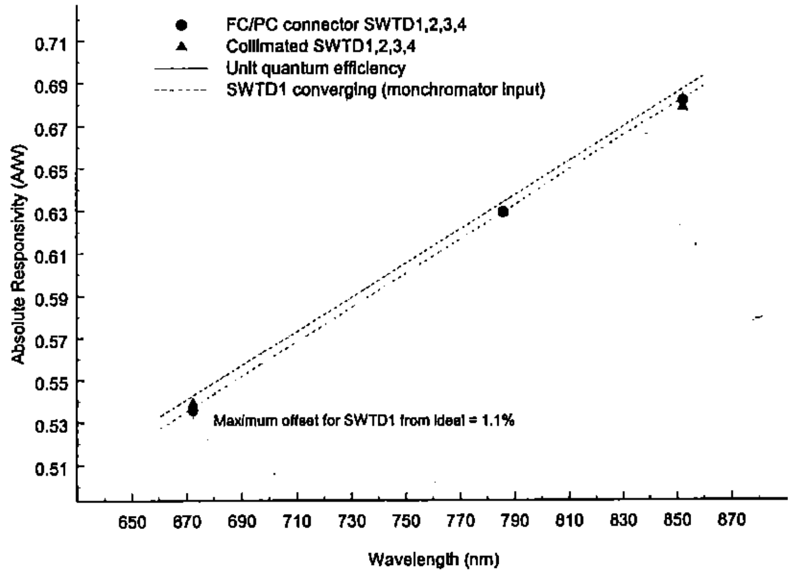

Figure 6. Absolute spectral responsivity for several input conditions of the SWTD compared with the ideal spectral responsivity of a PIN silicon photodiode.

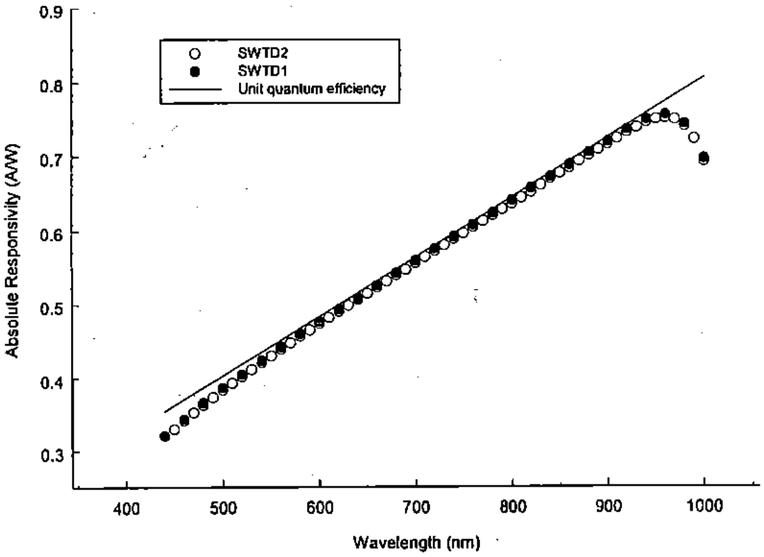

Figure 7. Monochromator-based absolute spectral responsivity of SWTD-1 and SWTD-2 (for clarity, some data points are not shown).

Table 1. Comparison of absolute spectral responsivity measurement results for SWTD-2 for several input conditions.

Wavelength (nm)	Laser-based, optical fibre with FC/PC connector (A/W)	Laser-based, collimated, open beam (A/W)	Monochromator-based, open beam (A/W)	Maximum difference from FC/PC results
672.2	0.5341	0.5364	0.5348	−0.43%
785.7	0.6301	0.6303	0.6270	0.49%
852.4	0.6797	0.6800	0.6801	−0.06%

We also measured the absolute spectral responsivity for a variety of input conditions as described in the introduction. The results of these measurements are shown in figures 6 and 7 and in table 1. We used collimated laser beams at 672.2, 785.7 and 852.4 nm and found that the absolute spectral responsivity was nearly the same as that measured using a lamp source and monochromator. With the same laser sources and the radiation transmitted through fibres and coupled with a variety of optical fibre connectors, the resulting absolute responsivity at each wavelength was

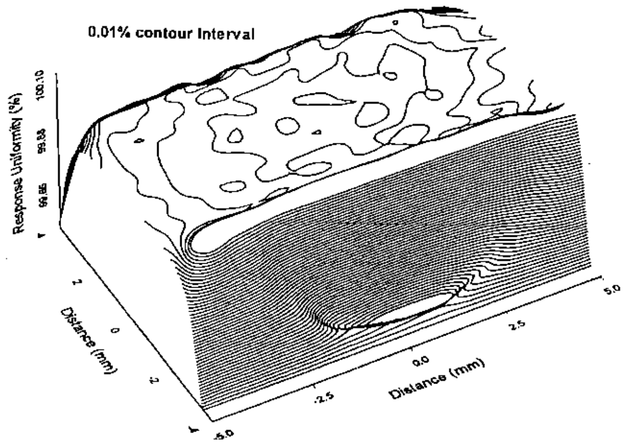

Figure 8. SWTD-1 spatial uniformity.

nearly identical to that obtained by the other means. The expanded uncertainty (using an expansion factor of $k = 2$) of the lamp and monochromator measurements was less than ±1.5%, and less than ±1% using the laser-based measurements systems.

5. Spatial uniformity

Knowledge of the spatial uniformity of a detector is particularly important for measurements that require varying beam input conditions (such as diverging versus collimated input beams or repeated detector alignment). We measured the spatial uniformity over the detector aperture area using a 2 mm diameter, circularly polarized, 633 nm laser beam as a probe. This probe beam was scanned across the aperture area while detector output data were collected at 0.5 mm intervals. In figure 8, the contour lines are spaced at 0.01% intervals and show that the variation in detector response is less than 0.02% over an area roughly 4 mm × 4 mm, and 0.04% over an area roughly 4 mm × 9 mm. The 'dish' feature at the front of the plot in figure 7 is a shadow of the front edge of the concave mirror.

6. Linearity

The nonlinearity of the wedge-trap detector, connected to a commercially available picoammeter, was characterized over the input power range of 1 nW to 10 mW at the wavelength of 859 nm. The data were acquired and analysed using the double-beam superposition method. By this method, the responsivity of the detector response was measured in sets of three using (1) an optical-power input P_A, (2) a nearly equal optical-power input P_B, and (3) the two optical inputs combined, P_C. This sequence was repeated several times over the optical-power input range. The electrical current I_A, I_B, and I_C, for each output was recorded for each input. The extent to which the detector–picoampmeter combination is linear was determined from the relationship $(I_A + I_B) = I_C$, over the input power range that was tested. The measured output current data were normalized to a calibration point and evaluated [8]. The responsivity as a function of input power varied less than 0.05% with an expanded uncertainty ($k = 2$) of ±0.1%.

7. Conclusion

The large field of view, high efficiency, and uniform spatial response demonstrate that our design will facilitate absolute spectral responsivity measurements necessary to calibrate optical-fibre power meters. The silicon wedge trap detector provides an accurate, versatile, and robust measurement tool that is insensitive to the input beam geometry for collimated and high divergence fibre-optic coupling devices in both the laboratory and the manufacturing environment. The physical structure of the detector is simple to fabricate and easy to calibrate, and in the future may be easily adapted to a variety of commercially available optical fibre connectors.

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