Accurate, inexpensive testing of laser pointer power for safe operation

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Abstract

An accurate, inexpensive test-bed for the measurement of optical power emitted from handheld lasers is described. The setup consists of a power meter, optical bandpass filters, an adjustable iris, and self-centering lens mounts. We demonstrate this test-bed by evaluating the output power of 23 laser pointers with respect to the limits imposed by the U.S. Code of Federal Regulations. We find a compliance rate of only 26 %. A discussion of potential laser pointer hazards is included.

Keywords: laser pointer, laser power, laser safety

1. Introduction

Handheld lasers (laser pointers) have been around for decades. However recent advances in laser technology have had a dramatic impact, enabling low-cost, high power laser pointers at a variety of visible wavelengths. These powerful lasers have found their way into society in large numbers and are being operated by people who may be unfamiliar with their potential for eye injury, resulting in increased reports of retinal injuries [1-3]. Previously published work toward establishing the conformity of laser pointers to power standards is limited in scope and dates back to over a decade ago [4]. In 2010, the Federal Office of Metrology in Switzerland issued a limited distribution report that documented significant non-compliance of a small sample of laser pointers [5].

More recently, we developed an inexpensive test-bed to characterize the output power of laser pointers in both the visible and infrared (IR) wavelength ranges with sufficient accuracy to determine compliance with the requirements of the U.S. Code of Federal Regulations (CFR). We have performed exhaustive calibrations of the test-bed's individual components to rigorously characterize the achievable measurement uncertainty for power measurements. However, the test-bed, consisting of low-cost commercial components, is simple in design such that it can be duplicated by a non-laser expert and used by institutions to test the CFR compliance of their laser pointers. Therefore, we also present a method for non-experts to achieve reasonable measurement uncertainty using the less-stringent specifications which are advertised by most manufacturers of these components. Finally, measurement results are presented for output power of 23 laser pointers purchased from a variety of sources, indicating the drastic degree to which "typical" laser pointers are out of compliance with current regulations.

1.1. *Laser pointer classification and safety*

Title 21 of the U.S. Code of Federal Regulations (CFR) [6,7] requires that handheld lasers used for pointing and demonstration purposes fall under the Class 3R laser hazard classification [8,9]. Table 1 illustrates the laser classification scheme. These types of handheld lasers — more commonly referred to as laser pointers — have become commonplace at conferences, trade shows, and classrooms used by individuals often unfamiliar with laser hazards. The human eye can transmit and focus light from 400- to 1400-nm wavelengths with an optical concentration power of approximately 100,000 [10]. In the visible spectrum (400 to 700 nm), the human aversion response to bright visible light can generally be relied upon to protect against potential injury from Class 3R lasers (power limit 5 mW). However, the aversion response cannot be relied upon for near-infrared (IR) wavelengths (700 to 1400 nm) where the human eye is less sensitive. Therefore, under the CFR, laser pointers are not allowed to emit hazardous levels of IR, and all IR emissions must remain below the Class 1 Accessible Emission Limit (AEL) [8,9]. In the IR, this limit is a function of wavelength (0.63 mW at 808 nm and 1.92 mW at 1064 nm) [8,9]. As with excessive visible light exposure, the most common eye injury from excessive near-infrared exposure is retinal burns [10].

More powerful Class 3B and/or Class 4 lasers are capable of inducing injury from even momentary exposure (< 0.25 s) [8,9]. In fact, the American Standard for the Safe Use of Lasers (ANSI Z136.1-2007) dictates the use of protective eyewear, designated laser control areas, laser hazard signage, and laser safety training for all Class 3B and Class 4 lasers, thereby prohibiting the use of these products for demonstration purposes by untrained users [8,9,11]. Confusion among consumers arises when Class 3B and Class 4 handheld laser products are advertised as

Table 1. Summary of Laser Classification under ANSI Z136.1-2007 and EN 60825-1-2007

Class 1	Non-Hazardous under normal use.
Class 2	Non-Hazardous under normal use for visible only lasers (400 nm to 700 nm).
Class 3R	Potentially Hazardous to the human eye under extended or fixated viewing conditions.
Class 3B	Hazardous to the eye and skin for direct and specular reflected beams.
Class 4	Hazardous to the eye and skin for direct, specular and diffuse reflected beams.

‘astronomy-grade’ or ‘military-grade’ laser pointers and are manufactured in a form factor similar to that of handheld demonstration lasers. Class 3B products may be hazardous under viewing conditions involving direct or specular reflected laser light even for momentary exposure [8]. Class 4 products pose skin and eye hazards from direct exposure or possibly diffuse reflections, and can pose fire hazards as well [8]. At present, there are few, if any, U.S. restrictions, e.g., user licensing requirements, on the sale of handheld lasers to the general public [12-17].

1.2 Red and green handheld laser construction

Recent advances in manufacturing of laser diodes have resulted in the proliferation of cheaper, brighter handheld lasers. The introduction of lower-cost, more reliable vertical-cavity surface-emitting laser (VCSEL) diodes has led to the more efficient production of red handheld lasers with emission around 650 nm [18]. Green handheld lasers are popular because they emit light very near the peak visual response of the human eye, such that even relatively low power levels can appear very bright. Most green laser pointers are based on diode-pumped solid-state (DPSS) technology, where an 808 nm pump laser diode is used to generate a 1064 nm fundamental in a Nd:YVO_4 or Nd:YAG crystal. The 1064 nm light then propagates through a potassium titanyl phosphate (KTP) crystal to generate a second harmonic at 532 nm. The combined light beams — 532, 808, and 1064 nm — are then collimated by the lens of the laser. In an optimal design, proper alignment and materials selection will confine IR emissions within the laser pointer housing. Typically, an additional IR blocking filter is placed at the output of the device to ensure that all external IR emissions are below the Class 1 AEL.

2. Principle of operation

The purpose of the NIST test-bed is to demonstrate an accurate and affordable approach for the characterization of the optical power spectrum of handheld lasers at visible wavelengths as well as common diode-pump (808 nm) and fundamental (1064 nm) wavelengths present in DPSS handheld laser devices. The test-bed is capable of power measurements at isolated wavelengths as well as the total spectral power output, suitable for characterizing the power output from a variety of handheld lasers. We use these measurements to evaluate NIST laser pointers for compliance with the CFR.

2.1 Test-bed design

The design goal was to assure clear, accurate, and repeatable test results as well as to enable safe operation by non-laser-experts. Therefore, the components were chosen to enable ease of laser alignment and wavelength selection, while simultaneously confining the laser light within the test-bed apparatus to eliminate exposure to potentially hazardous levels of stray light. The system, shown schematically in figure 1, is composed of a commercial laser power meter, two selectable bandpass optical filters, a lens tube, an adjustable iris, and two self-centering mechanical lens mounts. Since the Class 1 AEL in the IR is a function of

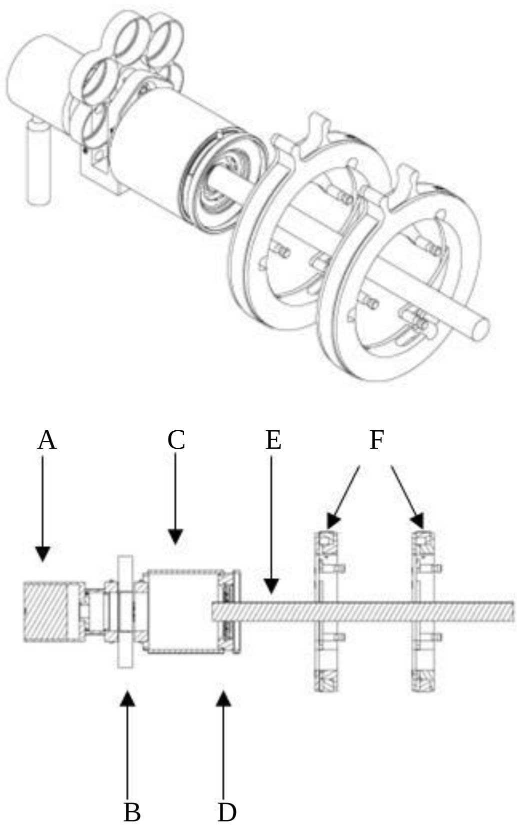

Figure 1. Schematic of test bed: side view (top) and top view (bottom). The handheld laser is mounted in the self-centering lens mounts. Bandpass filters are mounted in the filter wheel and can be used to isolate optical power at specific wavelengths. The adjustable iris, closed around the output end of the laser pointer, protects the operator from exposure to potentially hazardous levels of laser light. The laser under test is inserted slightly past the iris to allow the iris to close around the laser body.

Components listed: A. Laser power meter. B. Selectable filter wheel. C. 5 cm diameter lens tube. D. Adjustable iris. E. Laser under test. F. Self-centering lens mounts.

wavelength, the test bed must be capable of independent evaluation of individual IR power contributions. Therefore, bandpass filters were employed to characterize the pump (808 nm) and fundamental (1064 nm) emission from green handheld lasers. An adjustable iris was used to close around the laser body to prevent exposure to the operator of possible hazardous levels of laser light. The laser under test was mounted within the self-centering lens mounts to ensure repeatable laser alignment for various laser pointer sizes.

The components were chosen for availability and low cost. Where we describe performance requirements, they have been selected to meet the specifications of manufacturers of these types of equipment. Assembling the test-bed using equipment of the stated specifications should result in a power measurement with an uncertainty of 10 % or less.

2.2 Power meter selection

The power meter consisted of an optical detector and display unit. There are numerous commercial detectors capable of accurate power measurements from Class 3R and 3B lasers. The most commonly available detector types are photodiode, pyroelectric, and thermopile. While each detector technology has its merits, not all are optimal for our application. Photodiode detectors have a large dynamic power range; however, their spectrally dependent responsivity would require calibration for accurate measurements of optical power at multiple wavelengths. Pyroelectric detectors are thermal absorbers. When coated with spectrally flat absorbing material, the responsivity of a pyroelectric detector is independent of wavelength. However, the use of a pyroelectric detector would require modulation of the light source, increasing the cost and complexity of the measurement system. Thermopile detectors – with good long-term stability, spectrally flat responsivity, and ease-of-operation – were the best choice for our measurement application. Therefore, we recommend a thermopile detector with continuous wave measurement capability and better than 5 % uncertainty over a power range of ~100 μW to 500 mW over laser wavelengths from 530 to 1064 nm.

2.3 Optical bandpass filter selection

The optical bandpass filters selected for this measurement need to be able to accommodate the individual wavelengths generated in the DPSS lasers (the pump at 808 nm and the fundamental at 1064 nm). The 1064 nm bandpass filter selected had a central wavelength of 1064 nm ± 2 nm, with a full-width half-max bandpass of 10 nm. The filter for the pump wavelength (808 nm) had a central wavelength of 800 ± 8 nm, with a full-width half-maximum (FWHM) bandpass of 40 nm. For a filter with a Gaussian transmission spectrum, an off-the-shelf 10 % uncertainty in the transmission value can be assumed as long as the wavelength being tested is no more than 25 % of the filter's FWHM away from the center of the filter. This assumes the manufacturer's reported transmission value has an inherent uncertainty much less than 10 %.

2.4 Test bed calibration

To improve the accuracy of our power measurements (below the nominal 10 % uncertainty derived from manufacturers' specifications), we calibrated both filter transmission and detector responsivity as a function of laser wavelength. The filters were calibrated at NIST from measurements of the relative power transmission through the filter using a NIST diode trap detector [19]. A narrow-line doubled Nd:YAG laser at 532 nm, a Nd:YAG laser at 1064 nm, and a tunable Ti:Sapphire laser operating at 808 nm were used to measure the filter transmission at the three wavelengths commonly found in DPSS green laser pointers. Power emitted at the 532-nm line was not detectable after our 808-nm or 1064-nm bandpass filters indicating an isolation of at least 60 dB. A discussion of the filter transmittance calibration is given in Appendix A.

The commercial power meter was calibrated at NIST at multiple power levels and at multiple wavelength settings to characterize both the power linearity response and spectral dependencies, if any [20]. While the calibration factor of the power meter differed by 3 % between its two gain ranges, there was no measureable dependency on the wavelength setting, indicating a flat spectral response across the portion of the spectrum of interest. A discussion of the power meter calibration and its associated uncertainties is given in Appendix A.

Uncertainty estimates were assessed following the guidelines given by Taylor and Kuyatt (1994) [21]. After calibration, our system is capable of power measurements with a nominal uncertainty of approximately 1% over the full wavelength range of interest. However, for institutions with less stringent uncertainty requirements, this test-bed is capable of power measurements with approximately 10 % uncertainty when components with the following specifications are used: 5 % uncertainty in power for the laser power meter and 10 % uncertainty in transmission value for the bandpass filters. Discussions of the standard uncertainty components and calibration values for the spectral dependence, power dependence, and detector gain stage are given in Appendix A.

3. Measurements

The most common devices used for demonstration purposes are red and green handheld lasers. For the initial results presented in this paper, laser power from only red and green lasers was measured. However, this test-bed can be used to characterize the power output from other visible wavelength handheld lasers as well [22]. For both red and green lasers, the total unfiltered laser power was recorded. In addition, power measurements were recorded with the 808 and 1064 nm bandpass filters in place for the green lasers. For each power measurement, the laser was energized for 20 seconds. The output power of the laser was recorded as the maximum value displayed on the power meter during that time interval.

The power reading at each wavelength P'_λ was corrected according to the power meter's power calibration factor, C_n for the n^{th} gain stage; readings from measurements with the bandpass filters were corrected for the transmission of the bandpass filter, T_λ, as well to yield the corrected (true) power P_λ. When measuring a green laser, the corrected power output for the 532-nm laser line was calculated by subtracting the sum of the IR power components from the corrected value of the unfiltered measurement P_{total},

$$P_{808} = \frac{P'_{808}}{C_n T_{808}}, \quad (1)$$

$$P_{1064} = \frac{P'_{1064}}{C_n T_{1064}}, \quad (2)$$

$$P_{532} = \frac{P_{total}}{C_n} - [P_{808} + P_{1064}]. \quad (3)$$

For the single-wavelength red laser pointers, no bandpass filters were used; only the power measured from the unfiltered beam was recorded and corrected for the responsivity of the meter.

$$P_{red} = \frac{P_{total}}{C_n}. \quad (4)$$

The uncertainty analysis is discussed in Appendix A.

A total of 23 handheld laser devices were purchased from several commercial vendors. Each of these devices was advertised as a Class 3R laser device suitable for use as a demonstration pointer. Measurement results are shown in figures 2 and 3. In our sample, 6 of the 11 red laser pointers and 11 of the 12 green laser pointers emitted power in excess of the CFR limits (Class 3R visible AEL and Class 1 IR AEL) for handheld demonstration lasers. One green laser pointer had a measured output power in excess of 20 mW at both 532 and 1064 nm. The study by Blattner [5] reported comparable results for green laser pointers. Overall, we found that 74 % of the devices in the study were not compliant with the CFR.

4. Conclusion

The test-bed described here enables optical power measurement of handheld laser devices for verification of compliance with CFR and ANSI power output guidelines for safe operating use in otherwise uncontrolled venues. The extensive calibration performed here enables optical power measurements traceable to SI units with uncertainties of less than 1 %. However, this level of uncertainty is unnecessary for most users. In considering the output powers from the lasers which we found non-compliant with the CFR, all but two failed by a margin of greater than 15 % of the AEL. In fact, 48 % of the devices tested emitted more than twice the AEL at one or more wavelengths. This often drastic degree of noncompliance indicates that there is real risk of hazardous Class 3B exposure from misuse of noncompliant laser pointers labeled as Class 3R devices. It also indicates that the described laser power measurement system needs only an uncertainty of 10 % or less in order to identify 94 % of the noncompliant lasers in this study. Institutions interested in ensuring the safe use of laser pointers within their organizations could build the test-bed described here using "off-the-shelf" parts (meeting the specifications listed above) capable of uncertainties of 10 % or lower. The quadrature sum (formula A3) of the detector uncertainty (5 %) and the filter transmission value (max 10 %), will result in an uncertainty of approximately 10 %.

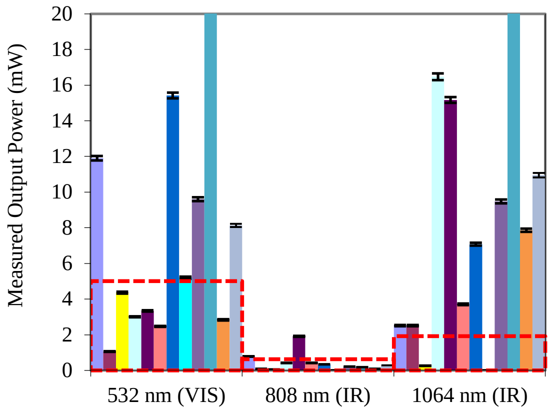

Figure 2. Measured output power of green laser pointers. Errors bars express the uncertainty for each power measurement. Vertical bars of the same color represent the power output at the three green laser pointer emission lines for a particular laser pointer. The red line represents the allowable emission limit (AEL) as a function of wavelength. The power output from 11 of the 12 devices exceeded the Class 3R limit at one or more wavelengths, and as such, they operated as *de facto* Class 3B devices, i.e., their laser hazard labels were incorrect.

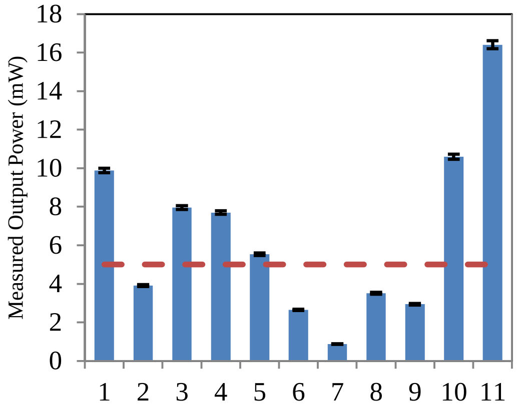

Figure 3. Measured output power of red laser pointers. Error bars express the uncertainty for each power measurement. The dashed red line represents the Class 3R visible AEL (5 mW). Each of these pointers was labeled as a Class 3R device. However, the power output from 6 of the 11 devices exceeded the Class 3R limit and, as such, they operated as *de facto* Class 3B devices, i.e. their laser hazard labels were incorrect.

5. Acknowledgments

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APPENDIX A

The uncertainty estimates in this paper follow the standard practices for NIST laser power calibrations and are assessed following guidelines of Taylor and Kuyatt [21]. To establish the uncertainty limits, the error sources are separated into "Type B" standard uncertainties, whose magnitudes are determined by subjective judgment or other non-statistical methods, and "Type A" standard uncertainties, whose magnitudes are obtained statistically from a series of measurements.

The Type A standard uncertainties are assumed to be independent and normally distributed, and consequently for N measurements with a standard deviation S_r, the standard deviation of the mean is $S_r/N^{½}$. In this paper, a Type A standard uncertainty was calculated for each laser pointer under test based on repeated power measurements.

The uncertainty, U, is determined by combining the Type A and Type B standard uncertainties in quadrature and is expressed as

$$U = \sqrt{\sum \sigma_i^2 + \sum \frac{S_r^2}{N}}, \qquad \text{(A2)}$$

where σ_i represents the three sources of Type B standard uncertainty: filter transmission σ_T, responsivity calibration factor σ_C, and spectral dependence, σ_S. Each of those uncertainty components is discussed in detail in the following sections.

A.1 Filter transmission

Bandpass filters were used to determine each of the individual spectral power components for the green handheld lasers at 532 nm, 808 nm, and 1064 nm. The value of the bandpass filter transmission is the ratio of the power measurement from a laser source incident on a NIST diode trap detector with the bandpass filter in place to the power measurement without the bandpass filter in place. Since the filter transmission is a relative measurement, the absolute responsivity of the NIST diode trap detector does not factor in to the measurement.

For measurement of green lasers, two bandpass filters were used: the first nominally centered at 800 nm with an approximate 40-nm bandwidth (FWHM), the second nominally centered at 1064 nm with an approximate 10-nm bandwidth (FWHM). The value of the bandpass filter transmission was determined at each of the principal spectral lines with one of the following sources: a narrow line doubled Nd:YAG laser at 532 nm, a Nd:YAG laser at 1064 nm, or a tunable Ti:Sapphire laser operating at

808 nm. The 532-nm source was used to determine any possible leakage transmission at the second harmonic. The Type B contribution σ_T due to filter uncertainty was less than 0.10 % (Table A1).

Table A1. Filter transmission T_λ, where λ is the filter center wavelength. The number of measurements at each setting was four. The overall Type B contribution was less than 0.10 %. It is represented in the uncertainty calculation as σ_T.

Filter Center Wavelength (nm)	Laser Wavelength (nm)	T_λ (%)	Standard deviation, S_r (%)	σ_T (%)
800	532	0.00	-	-
	808	79.66	0.13	0.10
	1064	0.00	-	-
1064	532	0.00	-	-
	808	0.00	-	-
	1064	70.27	0.01	0.07

A.2 Spectral dependence calibration

The power meter consisted of two components: a thermopile detector and a display unit for a visual reading of the detector signal. The display unit had manufacturer-supplied calibration factors stored in its erasable programmable read-only memory to convert detector voltage signals to power readings in units of watts. These calibration factors were a function of wavelength. A series of NIST calibration measurements were performed with a HeNe laser at a wavelength of 632.8 nm and 1 mW power to determine the spectral dependence of the detector. These results are summarized in Table A2. The differences in the calibration factors (with respect to the calibration factor at 633 nm) Δ_{633} were within the uncertainty of the NIST spectral-dependence calibration; therefore no data corrections for spectral-dependence were made. However, the standard uncertainty contribution σ_S of the spectral dependence calibration of nominally 0.45 % is factored into the uncertainty as a Type B contribution (Table A2). To estimate the uncertainty of the off-the-shelf system, the specific spectral-dependence component of the uncertainty needn't be specified as it will be contained in the overall absolute power meter calibration over the operating wavelength range.

Table A2. Spectral dependence of power meter's internal calibration factor using a 633 nm HeNe laser at 1 mW. Differences in the calibration factor from the value at 633 nm (Δ_{633}) were within the calibration's uncertainty. *T*herefore, no corrections for spectral dependence were made to the data. However, the standard uncertainty σ_S of the spectral dependence calibration is factored into the uncertainty.

Wavelength (nm)	Calibration factor (reading/W)	Standard Deviation S_r (%)	σ_S %	Δ_{633} (%)
532	0.9601	0.24	0.45	0.05
633	0.9596	0.25	0.45	0.00
808	0.9605	0.16	0.44	0.09
1064	0.9607	0.28	0.45	0.11

A.3 Absolute power meter calibration and linearity

An absolute calibration was performed on the power meter. The meter's two components – a thermopile detector and a display unit – were treated as a single unit for calibration purposes. The display unit had an internal gain-stage with a gain transition occurring at 3 mW as displayed on the unit's front panel. Therefore, a series of calibration measurements were performed at multiple power levels using a HeNe laser at 632.8 nm to determine the power linearity of the thermopile unit (Table A3). This nonlinearity is negligible but we include its uncertainty σ_{NL} in our estimate of σ_c below. There was a statistically significant difference (3 %) between the calibration factors for the two gain stages. Therefore, two calibration factors were determined: C_1 for power readings below 3.0 mW, and C_2 for readings equal to or greater than 3.0 mW. The standard uncertainty σ_C (0.56 and 0.43 for C_1 and C_2 respectively) from the absolute power calibration was factored into the uncertainty as a Type B contribution; values for the calibration factor and standard uncertainties are given in Table A.4. Again, for the off-the-shelf system uncertainty, the linearity contribution is already taken into account in the absolute power meter calibration over the full operating power range.

Table A3. Absolute power calibration factor *C*. The power meter was calibrated at several different power levels; the number of measurements at each power level was 4.

Power (mW)	*C* (reading/W)	Standard deviation, S_r (%)	σ_{NL} (%)
0.098	0.9610	1.20	0.74
0.579	0.9576	0.08	0.43
0.97	0.9585	0.48	0.49
4.81	0.9845	0.09	0.43
9.82	0.9856	0.19	0.44

Table A4. Calibration factor C_n of detector gain stages. The power meter had two range settings *n*; *n=1*, for power less than 3 mW and *n=2*, for powers greater than or equal to 3 mW. For each range, the calibration factor was determined by taking the mean value of *N* measurements, where *N*=12 for range 1 and *N*=8 for range 2. The standard uncertainty σ_C represents the standard deviation of the mean for a given range setting.

Calibration Factor	Display Unit Power Range	Calibration factor (reading/W)	σ_C (%)
C_1	< 3.0 mW	0.9590	0.56
C_2	≥ 3.0 mW	0.9851	0.43

A.4 Total uncertainty

For each laser pointer under test, the uncertainty was established solely by the Type B standard uncertainty for the measurement system
σ_B, where

$$\sigma_B = \sqrt{\sigma_T^2 + \sigma_C^2 + \sigma_S^2}. \quad \text{(A3)}$$

The standard uncertainties of the measurement system σ_B for each of the measurement system configurations are given in Table A5.

Table A5. Measurement system standard uncertainty σ_B as a function of measurement wavelength and power level.

Wavelength (nm)	Power range (mW)	σ_T (%)	σ_C (%)	σ_S (%)	σ_B (%)
532	< 3.0		0.56	0.45	**0.72**
532	≥ 3.0		0.43	0.45	**0.62**
650	< 3.0		0.56	0.45	**0.72**
650	≥ 3.0		0.43	0.45	**0.62**
808	< 3.0	0.10	0.56	0.45	**0.73**
808	≥ 3.0	0.10	0.43	0.45	**0.63**
1064	< 3.0	0.07	0.56	0.45	**0.72**
1064	≥ 3.0	0.07	0.43	0.45	**0.62**

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