A sensitive and high dynamic range cw laser power meter

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We report the design of a cost effective, highly sensitive cw laser power meter with a large dynamic range based on a photodiode. The power meter consists of a photodiode, a current to voltage converter circuit, an offset balancing circuit, a microcontroller, an analog to digital converter, reed relays, and an alphanumeric liquid crystal display. The power meter can record absolute laser power levels as low as 1 pW. The dynamic range measured with a cw laser at a wavelength of 532 nm is 8×10^{10}. The high sensitivity and large dynamic range are achieved by the implementation of an analog background balancing circuit and autoranging. © *2008 American Institute of Physics.*
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I. INTRODUCTION

Laser power meters are widely used in the laser laboratories to monitor the cw and average power of high repetition rate pulsed lasers. These can be categorized broadly into thermal and quantum detector based power meters. The power meter based on thermal transducers such as thermopile or pyroelectric detectors are slow in response, costly but have flat spectral response.

Quantum detector such as photomultiplier tubes, photoconductors, and photodiodes (PDs) is widely used to measure low power levels due to the following advantages: excellent linearity of output current as a function of incident light intensity, large responsivity, low noise, rugged to mechanical stress, low cost, compact, light weight, long lifetime, and high quantum efficiency. In general photomultiplier tubes require high voltages for their operation. On the other hand, silicon PDs can function at low voltages.

A PD can be connected in parallel with a simple resistor. When light falls on the PD, its shunt resistance drops exponentially. The output voltage varies logarithmically with the input light in this mode of operation. A PD can also be reverse biased in series with a load resistor. When the light falls on the PD, the dynamic reverse biased resistance remains constant. The generated photocurrent is proportional to the incident light flux and a voltage is measured using a load resistor. In this photoconductive mode of operation, the output voltage measured across the load resistor remains linear with input light. A PD-operational amplifier combination can be used either in voltage mode or current mode of operation.[1] Voltage mode of operation has a nonlinear response and the current mode of operation has a linear response with the incident light.[1] However, in the reverse mode of operation the dark current and other mechanism of noise limit the sensitivity at low light level. The power meter based on PDs has fast response and is cheap compared to a thermal detector. However, the responsivity of these detectors is wavelength dependent.

Typically PDs can easily measure the laser powers from micro- to milliwatt range. However, the laser power less than few nanowatts are difficult to detect due to the presence of large background signal. The inherent noise in the circuit also poses serious limitation in the measurement of low powers. Laser power meters developed using various sensors are described in Refs. 2–7. A microprocessor based photometer and its calibration with various sources is described in Refs. 8 and 9. A photoacoustic cell based power meter with a large dynamic range of 2×10^6 for a cw argon laser is reported in Ref. 3. PD based commercial OPHIR power meter (model PD-300) with Patent No. 5376783 (Ref. 10) can measure power from about 10 pW to 300 mW. This power meter uses two PDs. The first PD measures the background light and the second PD records sum of the signal and the background light. The output signal is the difference signal from the two PDs. In this paper, we describe a power meter with a large dynamic range and high sensitivity which is based on a single PD. A tube in front of PD reduces the stray light. We have designed an offset balancing circuit to compensate for the dc and low frequency noise of electronic circuit and to reduce the background noise due stray light. The power meter can record absolute laser power levels as low as 1 pW. The dynamic range measured with a 200 mW cw laser at a wavelength of 532 nm is 8×10^{10}. The power meter has microcontroller with autoranging capability and digitally displays absolute power after calibration.

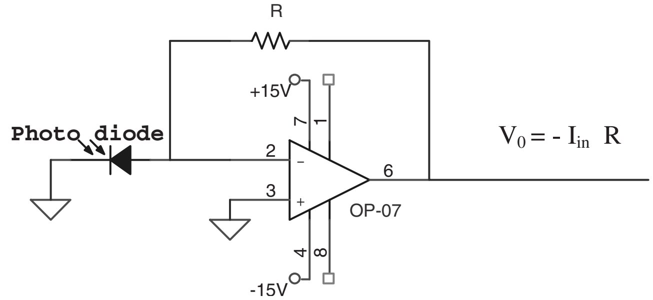

FIG. 1. The basic block of the current to voltage converter circuit with the PD.

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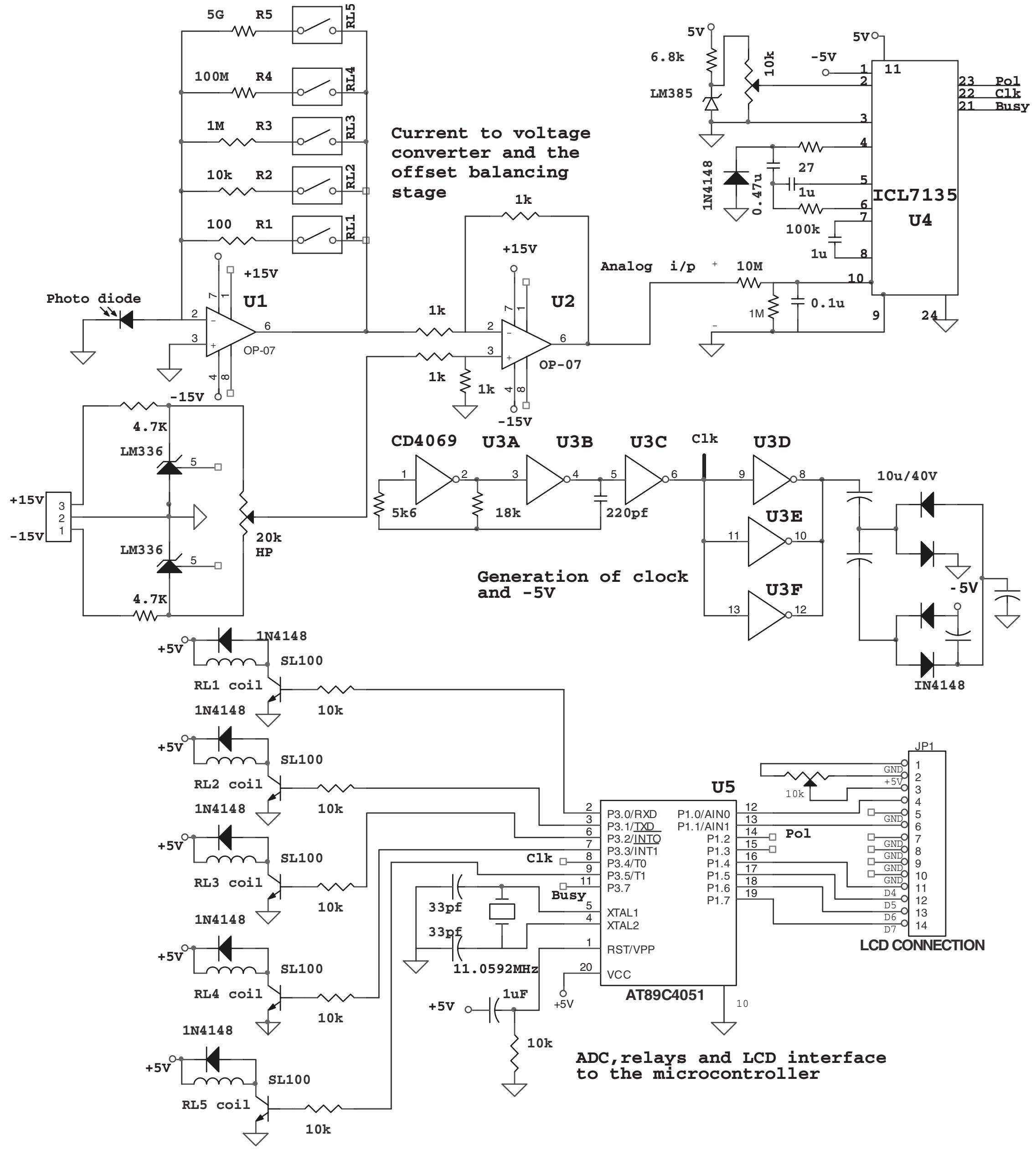

FIG. 2. Complete circuit diagram of the cw laser power meter.

II. THEORY OF OPERATION

The principle of operation of the power meter is based on the conversion of incident laser light to a proportionate current by a PD and a current to voltage converter circuit. The basic circuit of the power meter is shown in Fig. 1. The PD converts the incident laser light to a proportionate current. The operational amplifier configured as a current to voltage converter circuit converts this current to a voltage. The PD in this circuit is operated in the current mode of operation without bias.[1] In current mode of operation, the current monitoring circuit should offer zero impedance to the PD. This condition is closely met by the zero impedance of the inverting input of the operational amplifier with the virtual ground. The high gain of the operational amplifier ensures the virtual ground condition at the inverting terminal which maintains the zero bias across the PD. The high input impedance of operational amplifier ensures that the entire PD current flows through the feedback resistor. For a known laser power, the current flowing through the PD can be estimated from the PD's responsivity data available in the data sheet. A laser light incident on the PD generates a current through it and the feedback resistor develops an output voltage equal to the PD current times the feedback resistor. The output voltage is given by $V_{out} = -I_{in}R$. Thus, the PD current (I_{in}) is converted to a voltage with the proportionality factor of the resistor.[11–17]

III. POWER METER CIRCUIT

Figure 2 shows the circuit diagram of the cw laser power meter. The main blocks of this power meter are a PD, a current to voltage converter, an offset balancing circuit, analog to digital converter (ADC), and a liquid crystal display

(LCD) . The power meter circuit requires ±15 and 5V dc for its operation. These input voltages are sourced by a commercial power supply powered from 230 V ac mains. The large area *p-i-n* PD S3590-01 from Hamamatsu with the operational amplifier OP07 (U1 in Fig. 2) and the feedback resistor converts the incident laser signal on the PD to an electrical signal. The feedback resistor of the current to voltage converter of the power meter (100 Ω, 10 kΩ, 1 MΩ, 100 MΩ, or 5 GΩ) is automatically selected by the autoranging circuit depending on the input laser power level. The output of the current to voltage converter stage is applied as one of the inputs to a difference amplifier stage employing the operational amplifier OP07 (U2 in Fig. 2). The second input to the difference amplifier is an offset compensating voltage variable from +5 to −5 V. The offset compensating voltages are obtained from the voltage reference (LM336) and a 20 kΩ Helipot. The output of the difference amplifier is digitized by a slow dual slope 4.5 digit ICL7135 ADC (U4 in Fig. 2). The ADC is configured to measure up to 19.999 V. The minimum and the maximum measurable ADC output values are limited by the operational amplifier's saturation voltages (about ±12 V for a ±15 V bias). The current to voltage converter and offset balancing stage are fabricated on a small printed circuit board (PCB) along with passive surface mount device components and this PCB is mounted in a small box of aluminum of size $10 \times 8 \times 8.5$ cm^3. The PD is mounted on the front side of the box. In the rear of the box is the knob for offset balancing Helipot (20 kΩ in Fig. 2), terminal block for the dc input and a BNC for the analog signal output.

To display the laser power and the automatic selection of the feedback resistor of the current to voltage converter, a microcontroller (atmel 20 pin 89C4051) (U5 in Fig. 2) and PCB mountable reed relays are added to the circuit, as shown in Fig. 2. The control of reed relays by microcontroller, automatically adjusts the feedback resistor, in accordance with the input laser power. The microcontroller is interfaced with three I/O devices: ADC, reed relays, and LCD. LCD is interfaced to the microcontroller by four data lines and two control lines. Reed relays are interfaced by five pins. The ADC is interfaced to the microcontroller with the help of BUSY, POLARITY, and CLOCK pins of the ADC.[18,19] The ADC runs at 10 kHz clock and the full ADC measurement cycle consists of 40 002 clock counts. The BUSY signal pin of ADC remains high until the unknown analog voltage and the reference voltage are present at the ADC integrator's input. The number of clock pulses during this time is counted by the microcontroller. The number of clock pulses proportional to the analog signal is obtained by subtracting 10 001 from number of pulses counted by the microcontroller. The number of clock pulses is converted to analog voltage by providing the conversion factor. The analog voltage is then converted to laser power in watts by the calibration factor in the software. Thus the laser power is displayed on the two lines × 16 characters alphanumeric LCD. The digitization and the display circuitry are placed in a separate box. The control software is written in KEIL C IDE for the operation of the power meter such as reading the BUSY signal HIGH, counting the number of pulses during BUSY signal HIGH, conversion from voltage signal to power in watts and the autoselection of feedback resistor of the current to voltage converter. The program is downloaded to the microcontroller through a programmer and serial port of the computer.

The calibration factor for each feedback resistor of the current to voltage converter is needed to display the power in watts. To estimate the calibration factor the input laser power versus the PD voltage was recorded separately for all the five ranges manually. These experimental data were fitted to a straight line passing through the origin. The slope of the line provides the calibration factor for each feedback resistor of the current to voltage converter. In autoranging mode, the measured power is calculated through software by using the calibration factor and the PD signal measured by the ADC.

The flow chart of the program loaded in the microcontroller is shown in Fig. 3. When a laser is incident on the PD, an analog signal proportional to the incident laser power is available at the output of the current to voltage converter. The control software sets the feedback resistor of the current to voltage converter as 5 GΩ and analog signal is digitized by the ADC. If the signal is less than 11 V, the analog voltage is converted to power by dividing with the calibration factor and displayed on the LCD in picowatts. If the analog signal is greater than 11 V, then the microcontroller with the help of reed relays changes the feedback resistor to 100 MΩ and analog signal is digitized by the ADC. If the analog signal is less than 11 V, the analog voltage is converted to power and displayed on the LCD in nanowatts. If the analog signal is still greater than 11 V, then the microcontroller with the help of reed relays changes the feedback resistor to 1 MΩ and analog signal is digitized by the ADC. If the analog signal is less than 11 V, the analog voltage is converted to power and displayed on the LCD in microwatts. However if the analog signal is still greater than 11 V, then the microcontroller with the help of reed relays changes the feedback resistor to 10 kΩ and analog signal is digitized by the ADC. If the analog signal is less than 11 V, the analog voltage is converted to power and displayed on the LCD in milliwatts. If the analog signal is still greater than 11 V, then the microcontroller with the help of reed relays changes the feedback resistor to 100 Ω and analog signal is digitized by the ADC. The analog voltage is converted to power and displayed on the LCD in watts.

IV. RESULTS AND DISCUSSIONS

The linear part of the response of the PD and hence the PD based power meter is determined in the large signal range by the saturation of the PD. The dynamic range can be further increased only by utilizing the low light level sensitivity of the PD. The dynamic range of a typical silicon PD is from 1 pW to 10 mW.[20] At the recording stage the lower limit is determined by the minimum detectable signal. To extend this range, that is, to measure low power signal, the resistor value is increased so that small laser signal or small current can generate sufficient signal for measurement. On the other hand at high incident laser power larger current and hence large voltage will be generated for very large resistor values. This may cause saturation of the output in the operational

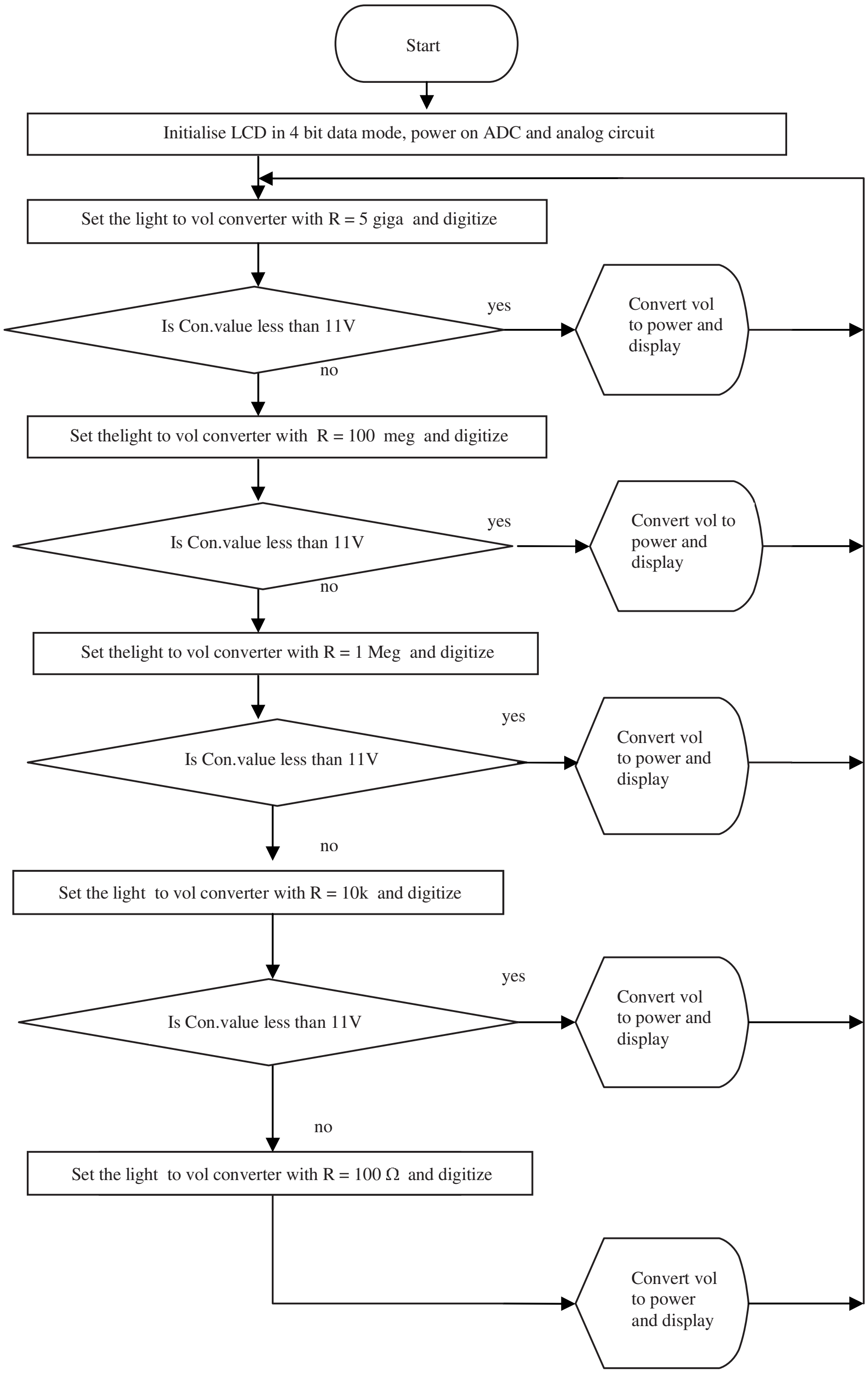

FIG. 3. Flow chart for the autoranging of the power meter.

amplifier. The noise of the electronic signal readout circuits generally sets a limit on the highest achievable sensitivity of the PD based power meters. We have used a general purpose OP07 in the analog circuit of the power meter and even with this low cost operation amplifier it is possible to measure power up to 1 pW. The performance of the power meter can be further improved by using operational amplifiers like OPA128 having low offset current (75 fA maximum), noise at 10 kHz (15 $\mathrm{nV/Hz^{1/2}}$) and low offset voltage (500 μV maximum) or OPA111 having low offset current (1 pA maximum), noise at 10 kHz (8 $\mathrm{nV/Hz^{1/2}}$), and low offset voltage (250 μV maximum) instead of OP07.

The extension of dynamic range of power meter with a single feedback resistor in the current to voltage converter stage has some limitations. In the low optical signal region, large feedback resistor of signal readout system is essential. However, in the large optical signal region, a large feedback resistor of the current to voltage converter stage leads to quick saturation of the readout part. Hence the autoranging, i.e., change in feedback resistor with input optical signal is necessary for utilizing the full dynamic range. We have increased the dynamic range and simultaneously increased the low light level sensitivity of the power meter using several modifications. The output voltage of the current to voltage converter of the power meter circuit depends on the magnitude of the feedback resistor (R1–R5) in U1 of Fig. 2. To increase the total effective performance of the system five different resistors were used. The various feedback resistors of the current to voltage converter of the power meter circuit for five different ranges are 100 Ω, 10 kΩ, 1 MΩ, 100 MΩ, and 5 GΩ. The resistors are automatically selected by the microcontroller depending on the input laser power. For low resistor value large input laser powers can be measured. For 1 GΩ resistor, a large signal appears at the output of the power meter due to background light. Thus, large resistor of this magnitude cannot be used in the standard current to voltage converter circuit.

Design modifications in the conventional current to voltage converter circuit are needed to incorporate large load resistor in order to increase the dynamic range and to measure low levels of power. The following design modifications were incorporated in the current to voltage converter circuit. An offset balancing circuit (U2 in Fig. 2)[21–23] helps to compensate for the background light and operational amplifier offsets. The offset balancing circuit alone is unable to compensate fully for the background light at low power levels. Therefore a 10 cm long anodized aluminum pipe of 3 cm diameter glued to the front of the PD housing helps to reduce the amount of the stray light falling on the PD. To measure the laser power, the incident laser beam is blocked to ensure that no laser light reaches the PD. The display would however show a low level signal depending on the background light level. The signal on the display is brought to zero by adjusting the offset balancing Helipot (20 kΩ in Fig. 2.) The signal recorded by the power meter is now free from the errors due to the operational amplifier offsets and the background light level.

If the offset balancing is carried at the highest sensitivity then the error at lower ranges of sensitivity remain negligible and additional manual adjustment is not required. This was experimentally verified in all the ranges. With better quality operational amplifiers with lower offset currents and voltages, this feature will further improve. To measure the dynamic range of the power meter, a 200 mW cw laser at a wavelength of 532 nm was used. The laser power incident on the PD is estimated by a commercial OPHIR NOVA power meter. The laser power incident on the power meter is scaled down by neutral density filters. The actual laser power incident on the power meter is obtained from the transmission factor of the neutral density filters. As the laser power is attenuated, the control of reed relays by microcontroller, automatically adjusts the feedback resistor of the current to voltage converter of the power meter, in accordance with the input laser power. The laser power recorded by the power meter is displayed on the LCD. Squares in Fig. 4 show the laser power recorded by the power meter as a function of input laser power. The experimental data was fitted to a straight line passing through the origin. The minimum and the maximum cw laser power measured in the linear regime were about 1 pW and 80 mW, respectively, which correspond to the dynamic range of 8×10^{10}. For a given feedback resistor of the current to voltage converter, the error between the measured power and the fitted value is about ±4%. The errors in the measurements depend on the variations in the transmission of ND filters, placing of the filters and the difference in sensitivity of PD at different positions. The errors would also result from variations in parameters of electronic components due to temperature fluctuations and deteriorations of the components with time. The background light in the laboratory and the large scattered light from the input laser source results in an output signal which cannot be completely compensated by the offset balancing circuit. Thus the background light and scattered light should be reduced to measure the low power signal.

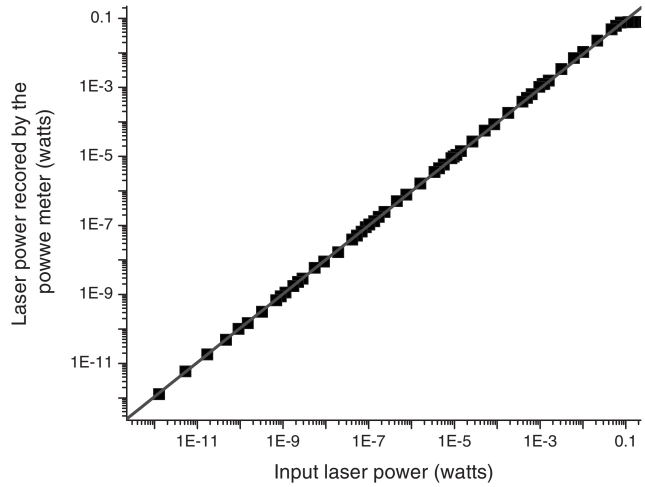

FIG. 4. The log-log plot of laser power recorded by power meter as a function of input laser power.

The power meter was also tested using a 10 mW cw diode laser at a wavelength of 642 nm. The minimum measurable power is about 1 pW. The measured dynamic range is limited to 1×10^{10} due to the maximum available laser power.

The response of the PD depends on the incident wavelength. Therefore, for the measurement of the laser power at any other wavelength the power meter should be calibrated with the commercial power meter. The reed relays used in the autoranging circuit can also be replaced by analog switches. However the analog switches may cause error in the measurements due to their high "on" resistance.

V. CONCLUSION

A cost effective, sensitive laser power meter with a high dynamic range capable of measuring a picowatt of cw laser power is demonstrated. Laser power up to 1 pW can be detected with a dynamic range of 8×10^{10} at a wavelength of 532 nm. The basic block of the power meter is the PD and the current to voltage converter. This provides an analog voltage proportional to the incident laser power. The offset balancing circuit is crucial in the measurement of low laser power. The conversion from the output voltage to the incident laser power is performed with the help of microcontroller via software. Thus the power meter displays the absolute value of the power on a LCD.

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