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Reinventing Thermal Laser Power Measurements

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Abstract

A novel design of a thermal laser power detector is presented, which allows minimizing the sensor dimensions, namely thickness and passive device area. The detector is intended to monitor medium laser power between 5 and 50 W. As its key feature, the sensor exhibits a rise time of just 200 ms, which is 5 times faster than conventional disc sensors. Such a low rise time is achieved by an axial thermopile arrangement combined with a minimized thermal mass.
In order to fully exploit the speed advantage of the new design, a specific optical absorber coating has been developed. The coating has a broadband absorption characteristic and damage threshold of 1.5 kW/cm2.

Keywords: Power monitoring; Thermopile; Absorption coating; Diagnostics and Control

1. Introduction

Laser systems exhibit variations of the light intensity over time. There are short term fluctuations due to the laser source stability and/or thermal drift [van Tartwijk 1998, Ready 1997, Narducci 1988]. These modulations are of the time scale of fractions of a second to hours. Additionally, the laser power drops in the course of the laser lifetime by up to 20% due to degradation of the active medium [Epperlein 2013]. The deterioration of optics aligned along the beam path cause a decrease in output power in the long term as well. Both types of power fluctuations might cause a lowered throughput due to defective products or additional maintenance down times. Hence, measuring laser power is a key requirement for effective beam control and reliable system operation.

Various detector types have been applied to monitor beam power and to set up a closed control loop for the laser power. While photodiodes are most commonly used for low power measurements in the visible spectrum, thermal detectors have proven useful for medium power ranges and are sensitive across a wide wavelength spectrum from UV to MIR. The most common type of thermal detectors is the thermopile disc [Villers 1969, Mefferd 1971]. With our detector design, two of the drawbacks of such sensors are addressed – their long rise time and their large passive area.

In the following, first the sensor design is introduced and compared to the conventional structure. Next, simulations based on a thermal model are presented which support the qualitative assumptions about the detector performance. Then, measurements of the rise time and the optical absorption spectrum of the coating are shown. Finally, a conclusion and an outlook for the application of the new sensor type are provided.

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2. Sensor Structure

2.1. Comparison between radial and axial sensor design

Fig 1(a) shows a top view of a conventional thermopile disc. Thermocouples are deposited onto an aluminum plate (typically ca. 1 mm thick) in a circular arrangement. All thermocouples are electrically connected in series and have one junction located at the edge of the inner circular area (hot junction) and one at the outer ring (cold junction). During operation, the inner area is illuminated by the impinging laser light. An absorber coating at the surface converts the incoming radiation into heat, leading to a temperature increase at the hot junctions. Since the outer ring is coupled to a heat sink, a temperature difference is built up across the junctions, which generates a thermoelectric voltage. The latter is directly proportional to the laser power and typically in the order of 600 µV/W.

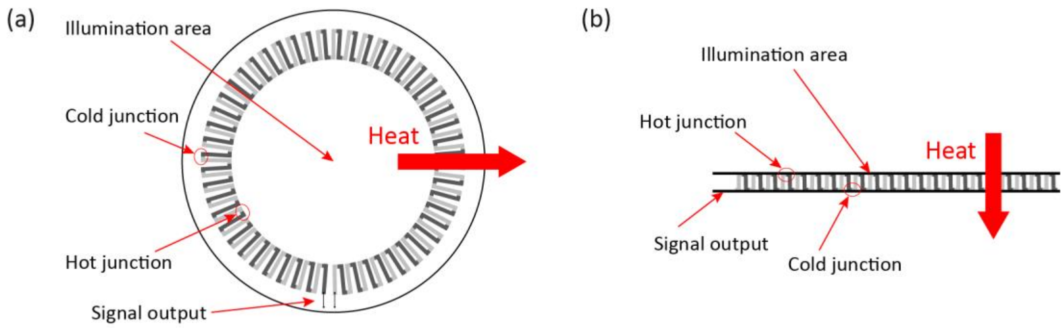


Fig. 1: Skteches of the two types of thermopile laser power detectors compared in this work. The arrangement of the thermocouples and the thermocouple junctions are indicated as well as the direction of heat transfer. (a) Radial thermopile disc; (b) Axial thermopile presented in this work.

A cross sectional view of the new detector design presented in this work is sketched in Fig 1(b). In contrast to the disc, the temperature difference is established between the top and the bottom of the detector. Thermocouples are embedded into a matrix and aligned vertically to the sensor surface forming junctions at the top and the bottom, respectively. As for the radial detector, the thermocouples are electrically connected to add up the voltages of the individual legs, yielding voltage signals of comparable magnitude to the disc (ca. 500 µV/W) under illumination.

After introducing the structural differences of the two detectors, now the implications of the design for the detector performance are discussed. In order to reach the full signal amplitude, the system needs to be in a thermal equilibrium i.e. the temperature difference between the hot and the cold junction needs to be constant. Hence, the rise time of the detector is directly related to the time required to reach thermal equilibration. In the conventional detector, heat transfer takes place along the thermocouples in radial direction. The thermopile disc exhibits rather large structures (see Tab 1), which result in both a large thermal mass and a large thermal resistance. Such a system has a slow transient thermal behavior. For the axial detector, the dimensions of the thermocouples are significantly reduced in order to lower the thermal mass. The short heat path and the low thermal capacitance lead to a major improvement of the signal rise time as will be proven below. The packaging and mounting methods of the detector also need to be carefully chosen in order to optimize the performance. Especially the thermal coupling to the top and bottom package is crucial.

From an application point of view, the sensor dimensions should be considered as well. The disc detector exhibits a large passive area (ca. 90%), which is not illuminated. For the axial detector the complete surface can be illuminated, meaning that it does not exhibit any passive area. An appropriate detector integration can therefore fulfill the demand for a compact measurement unit.

The absorber coating is located on the upper side of the detector and converts the impinging radiation power into heat. The quality of a thermopile detector depends strongly on this coating. An ideal coating has a flat and high (>80%) absorption throughout the wavelength spectrum from UV to MIR. Additionally, it is robust against mechanical impact and high power densities of the incoming light. In order to maintain the improved rise time of the device, a coating that can be applied to the detector surface directly as a thin layer was developed.

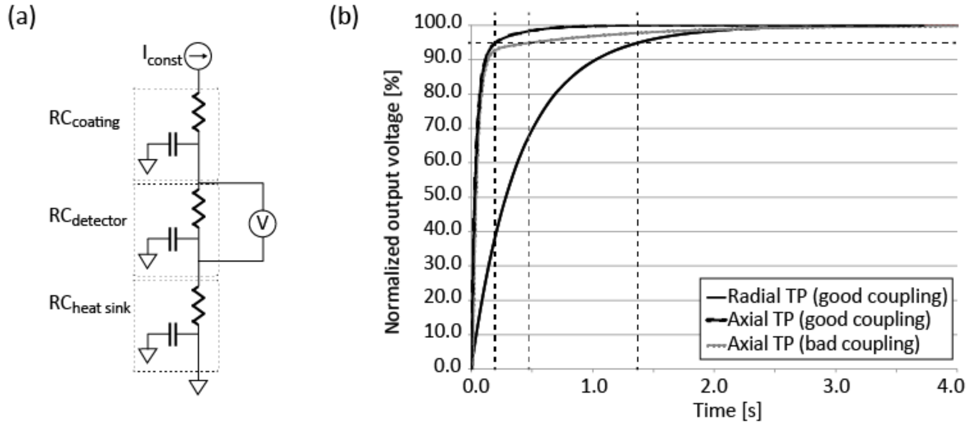
3. Thermal Model

In this section the above arguments are underpinned with a basic thermal model which has proven very helpful for understanding the influence of the detector geometry on its transient behavior. The thermal properties of all elements of the laser power detector are described by using an electric equivalent circuit as analogon and simulate the resulting rise time of the signal. In the model the electrical resistors and capacitors describe the thermal resistances and capacitances. Incident light is modelled by a current source. The resulting temperature differential across a thermal resistor due to the absorbed laser power is measured by a voltage probe in the equivalent circuit. The conversion of the temperature differential across the detector and the thermoelectric voltage output signal is made by multiplying the temperature difference by the thermocouple Seebeck of the detector and the number of thermocouples.

The detector itself can thermally be modeled as a thermal *RC* circuit element consisting of a thermal resistance and a thermal capacitance. It is coupled to the absorber coating at the illuminated side and to the heat sink on the other side, which both constitute thermal *RC* elements as well. The incident light can be modelled as a constant current source at the terminal of the coating. For the read-out, the relevant parameter is the temperature drop across the detector element ($RC_{detector}$), since the output signal of the detector is directly proportional to this value. The equivalent circuit for the thermal model is displayed in Fig 2(a).

Simulations were carried out with LTSpice and three different scenarios were compared. First, the influence of the design difference between the radial and the axial sensor is investigated. In the applied model, the detector resistance and the capacitance capture the difference between the two structures. The thermopile legs of the radial detector are orders of magnitude longer than for the axial design and therefore display a considerably larger thermal resistance. At the same time, the thermal capacitance of the each leg is higher as compared to the axial detector. Based on the geometry and the used materials, the resistance is estimated to be 2 times larger and the capacitance to be 10 times bigger than for the axial detector. In a first step, an optimal coupling to the coating at the top side and to the heat sink at the bottom is assumed.

Fig 2: (a) Lumped element circuit used for the thermal model of the thermopile laser power detectors described in this work; (b) Simulation results for



three different scenarios, namely the radial thermopile disc (TP), a well coupled axial thermopile and a thermopile coupled poorly to the heat sink. The time-dependent voltage signal is displayed.

The simulation results are displayed as two black curves in Fig 2(b), where the probed signal is shown as a function of time. Both curves show a steep rise of the signal which then saturates at a constant value. Commonly, the rise time is defined as the time it takes the signal to reach 95% of its full amplitude and this convention is followed here. The resulting values are 0.25 s and 1.4 s for the axial and the radial detector, respectively. This supports the statements made in the previous section in a more quantitative way.

Further, the model is used to investigate the influence of the thermal coupling to the heat sink. As can be seen at the example of the grey curve in Fig 2(b), a 4 times higher thermal resistance of the heat sink leads to an almost doubled rise time.

Although based on very basic assumptions about the system, the thermal model presented here is a valuable tool for the identification of crucial design factors. The findings from the simulations have been used to optimize the detector design and mounting. The fabrication process is described in the next section.

4. Fabrication

4.1. Detector element

The sensor fabrication relies mainly on wet chemical processes that were adapted from the printed circuit board (PCB) industry. For both the detector structure and its fabrication process, patents have been filed.

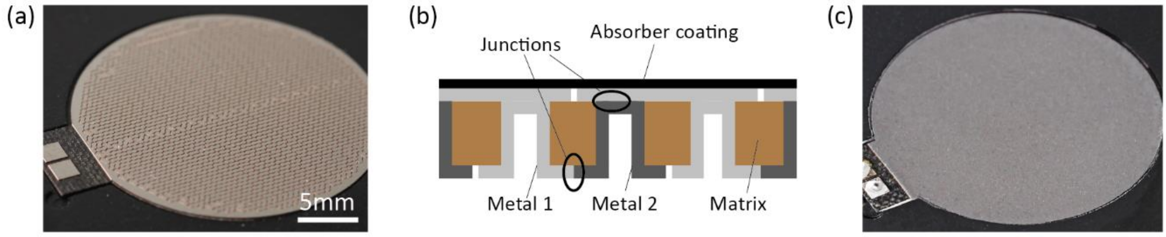


Fig 3: (a) Axial thermopile detector before the application of the optical absorber coating; (b) Sketch of a cross section of the detector displaying the different layers; (c) Final detector element with absorber coating.

A fiber-filled high-Tg epoxy laminate is the supporting material of the sensor structure. A plurality of copper-plated blind via-holes is then created by means of laser structuring and electrochemical copper deposition. Besides constituting the first thermoelectric material, the copper vias allow to electrically and thermally connect both sides of the laminate without compromising the continuity of the sensor surface. Conventional through-hole drilling would lead to a similar functionality, but due to the perforated top surface, the application and continuity of the absorber coating would be compromised. The thermal pathway of the power incident on the inside of the holes would also be very ill-defined.

The next step is the laser-drilling of the second thermocouple holes. This process is performed analogically to the blind via creation mentioned above, but this time with nickel instead of copper plating, thereby forming the second thermoelectric material. The thickness and quality of the metal layers were carefully tuned to obtain the best thermal properties of the structure.

Subsequently, both sensor surfaces are structured by lithographic techniques to reveal the series connection of all thermocouples. The bare sensor element is depicted in Fig 3 (a) and a sketch of a cross section is shown in Fig 3 (b). The sensor is then coated with the absorber coating (described below) and the detector is finalized by hot-pressing the laminate onto a heat sink by means of a thermally conductive adhesive. As was shown in the simulations, ensuring an optimal thermal coupling is crucial for the detector performance.

4.2. Absorber coating

All components of the optical absorber coating are inorganic and applied with a spray process directly onto the sensor surface. Subsequent thermal annealing cycles ensure robustness against chemical and mechanical impacts i.e. against all common cleaning agents and the further processing in a hot press. As can be seen in Fig 3(c), the surface is rather rough and therefore scatters light diffusively, improving the absorption characteristics.

5. Experimental Results

5.1. Rise time

Measurements of the detector rise time have been carried out with several laser systems to ensure the repeatability at different wavelengths and laser powers. In the following, representative data taken with a 1 W CW laser at 1064 nm is presented. The beam diameter was set to 15 mm during the experiment to illuminate the detector area for the most part. For the data acquisition, a high resolution voltmeter was used to log the time dependent voltage signal. As a reference, a thermopile disc detector was characterized as well. Care was taken to ensure a good thermal coupling of both detectors to the heat sink.

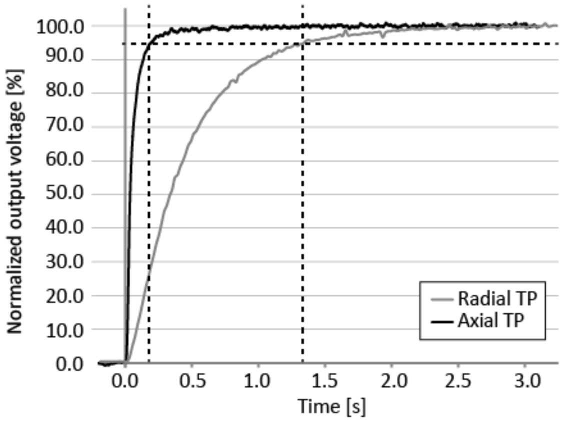


Fig 4: Transient behavior of two thermopile detectors. The voltage signal was recorded with a sampling rate of 2000 Hz.

In Fig 4 the output signal is plotted for the two detectors. Both signals have been normalized to facilitate the extraction of the rise time value. Whereas the radial disc crosses the 95% line after 1.34 s, it takes only 195 ms for the axial thermopile to reach this point. Hence, the rise time is a factor of 6 lower for the axial detector. This finding is in strong agreement with the assumptions stated above which were based on the sensor structure.

Tab 1 summarizes the geometric properties and the performance of the two detector types compared in this work.

Table 1. Comparison between radial and axial detector (dimensions and performance)

	Radial thermopile	Axial thermopile
Sensor thickness [mm]	0.5	0.25
Thermocouple length [mm]	6	0.2
Sensing area (diameter) [mm]	12	26
Sensor passive area [%]	90	10
Output voltage per Watt [µV/W]	600	500
Max. power [W]	50	50
Rise time (0-95%) [s]	1.34	0.2

5.2. Spectral absorption and damage threshold

For the characterization of the absorber coating, both the spectral absorption and the threshold for the power density have been tested. The latter has been determined to be 1.5 kW/cm^2, corresponding to a 10 W beam focused to a radius of ca. 0.9 mm. In applications where a higher power density is used, the beam needs to be defocused for the measurement.

The results for the spectral absorption are shown in Fig 5, where the range between 190 nm and 15 µm is covered. Up to 8 µm the absorption is larger than 80% and in large wavelength ranges flat. Changes of the absorption of less than ±5% occur in this wavelength range making it a good candidate for the application in tunable lasers as well.

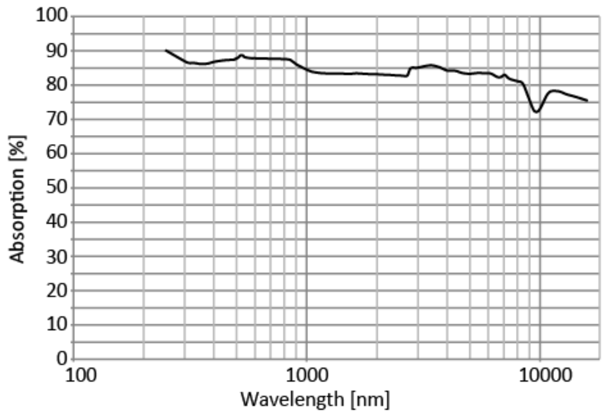


Fig 5: Absorption characteristics as a function of wavelength. The range from 190 nm to 15µm has been measured.

6. Conclusion and Outlook

In this work, a new design for a thermopile laser power detector has been presented. By carefully tuning its thermal properties, namely the thermal resistance and capacitance, the rise time is improved by a factor of 6 as compared to a conventional thermal laser power detector. A simple thermal model of the system allows to understand the influence of material and design parameters of the sensor module. The model confirmed the great importance of thermal coupling between sensor device and package when further integrated.

A fast detector like the one presented here is beneficial for all measurement and control applications e.g. in industrial laser systems. Since feedback is provided fast, reproducibility and throughput are increased.

The patented fabrication process enables flexible modification of detector size and performance parameters. Hence, an adaptation to the specific requirements of new applications can be readily accomplished.

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