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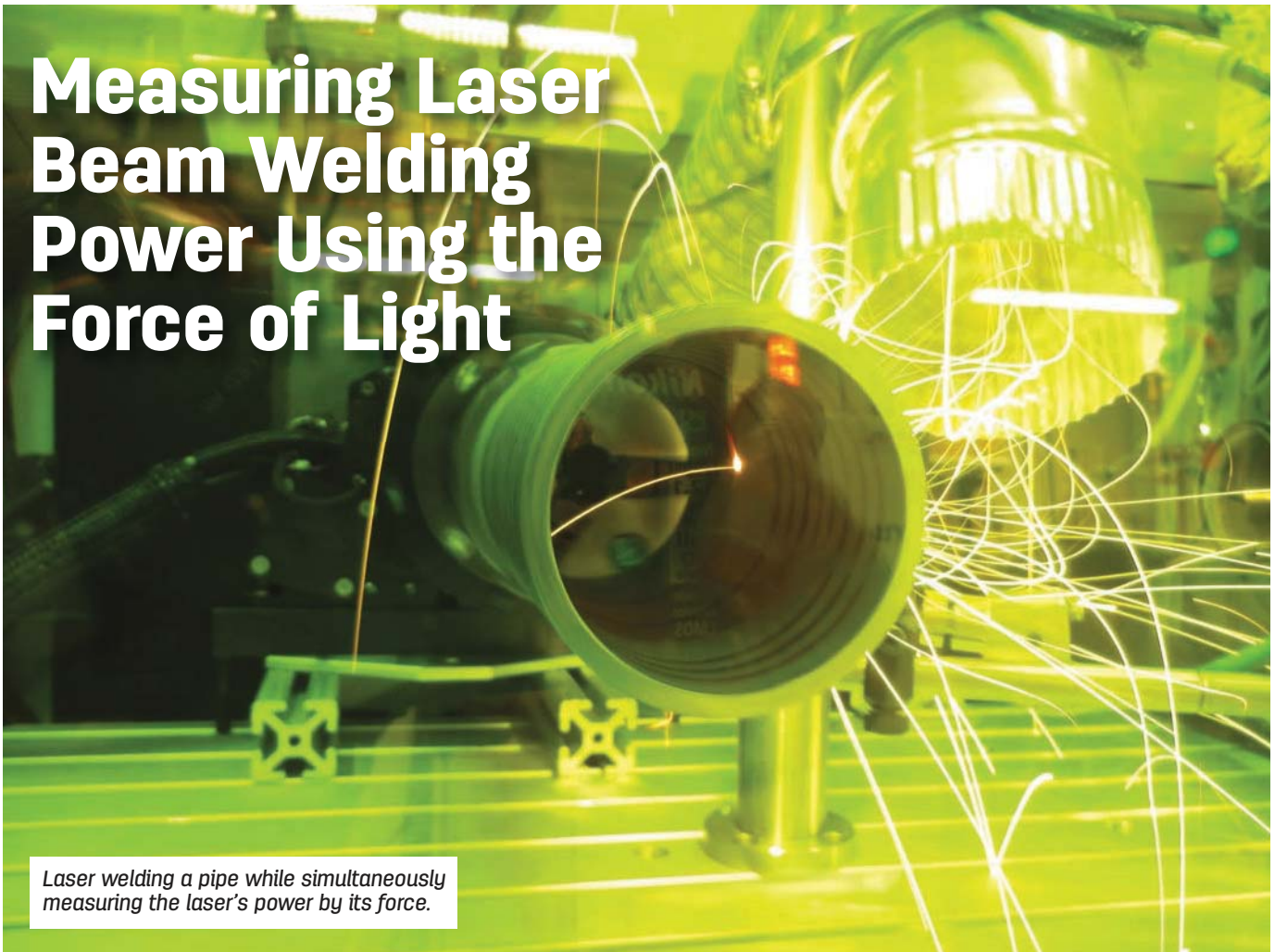
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Measuring Laser Beam Welding Power Using the Force of Light



Laser welding a pipe while simultaneously measuring the laser's power by its force.

A novel optical laser-power measurement technique offers high accuracy in real time

BY PAUL WILLIAMS, JEFFREY SOWARDS, AND BRIAN SIMONDS

What could be more fun than welding with a laser? The idea of a beam of invisible (infrared) light powerful enough to melt metals such as steel and aluminum is not only intriguing but very practical. Laser beam welding takes advantage of the unique delivery mechanism of laser light in order to provide high energy density, deep penetration, minimal heat-affected zone, and the ability to weld at a distance from the workpiece. However, laser beam welding also brings with it new challenges in terms of characterizing

the operating parameters. The most fundamental of these is the optical power delivered by the laser. Currently, there are two basic approaches to measure the laser power delivered to the welding work surface, but both have limitations. It comes down to a tradeoff: either the laser's power can be measured accurately but not during the weld process, or it can be measured in "real time" while welding is taking place, but with greatly reduced accuracy. The benefit of both accurate and real-time power measurement would be a great improvement in

laser-welding quality monitoring, especially when precise power delivery is required for critical welding applications such as aerospace manufacturing. In response to this need, the National Institute of Standards and Technology is developing a new way to measure laser power that allows both accurate and real-time measurements of laser welding power.

Traditionally, accurate measurement of high laser powers involves measuring how much heat is delivered. Typically for this purpose, a "thermal" power meter is used. In principle, the

defocused laser beam is directed onto the surface of the thermal power meter, which is coated by a substance that is highly efficient at absorbing light at the wavelength of the laser beam. The meter then operates by absorbing all the laser light and measuring the resulting temperature increase. This means the laser power is being used in the measurement and is not available for the welding process. We are approaching the measurement of high laser powers in a different way. Instead of absorbing all the laser light, we prefer to reflect as much as possible from a mirror. And, rather than measuring heat, we measure the very small force of the light as it pushes on the mirror. It may be surprising that light itself can push on anything, but as will be explained, this idea of "radiation pressure" has been proven repeatedly, and is used in other scientific fields. The idea of measuring high-power lasers without appreciable heating then opens several inviting possibilities. With a radiation pressure power meter, the laser power could potentially be measured to within 1–2% accuracy during the welding operation and would allow for quality monitoring and could simplify the set-up process for a weld.

We have done preliminary testing of this idea by welding with an ytterbium fiber laser at up to 5 kW optical power while simultaneously and accurately measuring the laser's output power using a prototype radiation pressure power meter. To our knowledge, this is the first such measurement of its kind.

Exploiting the Force of Light to Measure Laser Welding Power

Since the 1700s, scientists have predicted that light has a momentum associated with it. This means that like any other travelling object, when light hits something, it pushes on it, but it was not until the early 20th century that this tiny push was actually measured. Of course, the push (or force) is very small. As a simple analogy, picture a tennis ball thrown toward a nonmoving racket — Fig. 1. The ball will bounce away, while the racket is pushed in the opposite direction. The force experienced by the racket will be in proportion to the mass of the ten-

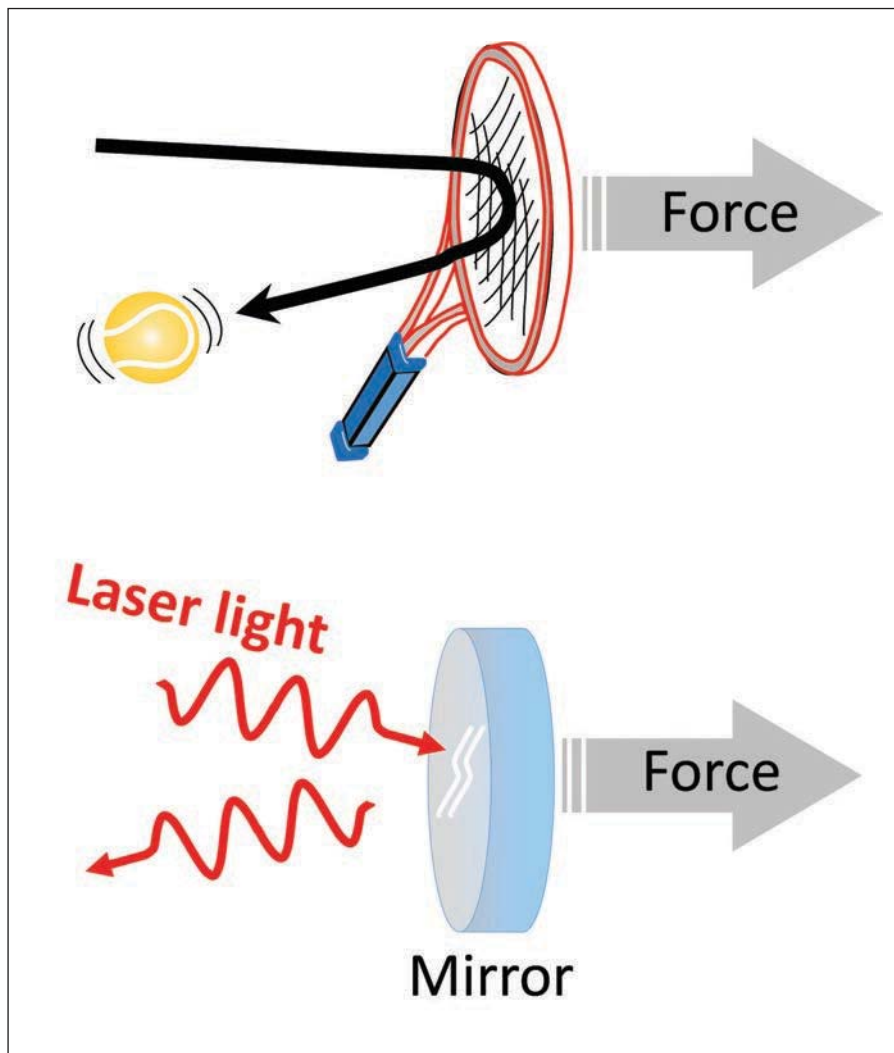


Fig. 1 — Just as a tennis ball bouncing off a racket pushes the racket back, light also pushes with a measurable force when it reflects off a mirror.

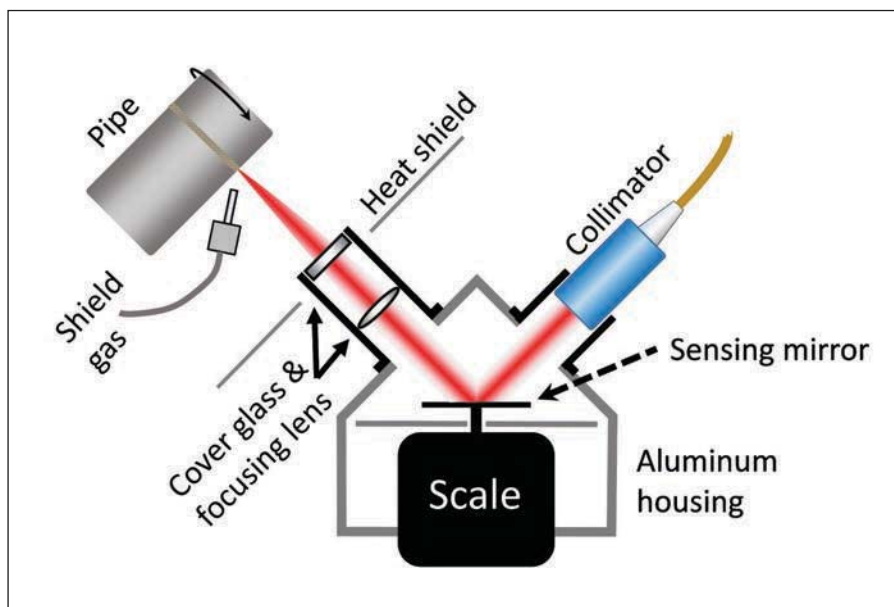


Fig. 2 — Diagram (overhead view) of radiation pressure power meter (RPM) in place for laser welding of stainless steel pipe.

nis ball and how fast it is moving. In the same way, when light reflects from a mirror, the mirror is pushed. Since all light travels at the same speed (about 299,792 km per second), the force felt by the mirror will depend only on the number and energy of the photons (light particles) hitting it in a given amount of time. (Think of billions of trillions of infinitesimally small tennis balls hitting the mirror every second). It turns out the force on the mirror is conveniently proportional to the optical power of the laser light that is being reflected. While this effect may seem insignificant, there are several familiar examples of radiation pressure. For instance, the tail of a comet points away from the sun in part due to the radiation pressure from the sun pushing on the gas and ice that make up the tail; spacecraft on long missions must correct for the force of sunlight in order to arrive at their target; and microscopic objects are manipulated by the force of light in a technique known as “optical tweezing.”

With increasing numbers of high-power lasers (1 kW and above) being used in laser welding operations, and the availability of scale technologies that can accurately measure changes in mass as small as 1–10 μg , radiation pressure can be easily measured. Practically, we have found that for multikilowatt lasers, their force on a mirror can be measured simply with a commercial scale.

Putting Theory Into Practice

We use a prototype device that we call a “radiation pressure power meter” (RPM) based on a commercially available mass-measuring scale and a high-quality (Distributed Bragg Reflector) mirror that reflects more than 99.9% of the incident laser light. The scale has a unique design that allows it to operate sideways (that is, unlike conventional scales that measure a force in the downward direction, this scale can measure a push in the horizontal direction). The scale can sense a change in mass as small as 10 μg . By reflecting the welding laser light from a mirror that is attached to the scale, we can measure the force imparted by the light without absorbing the light (less than 0.1% is absorbed). By

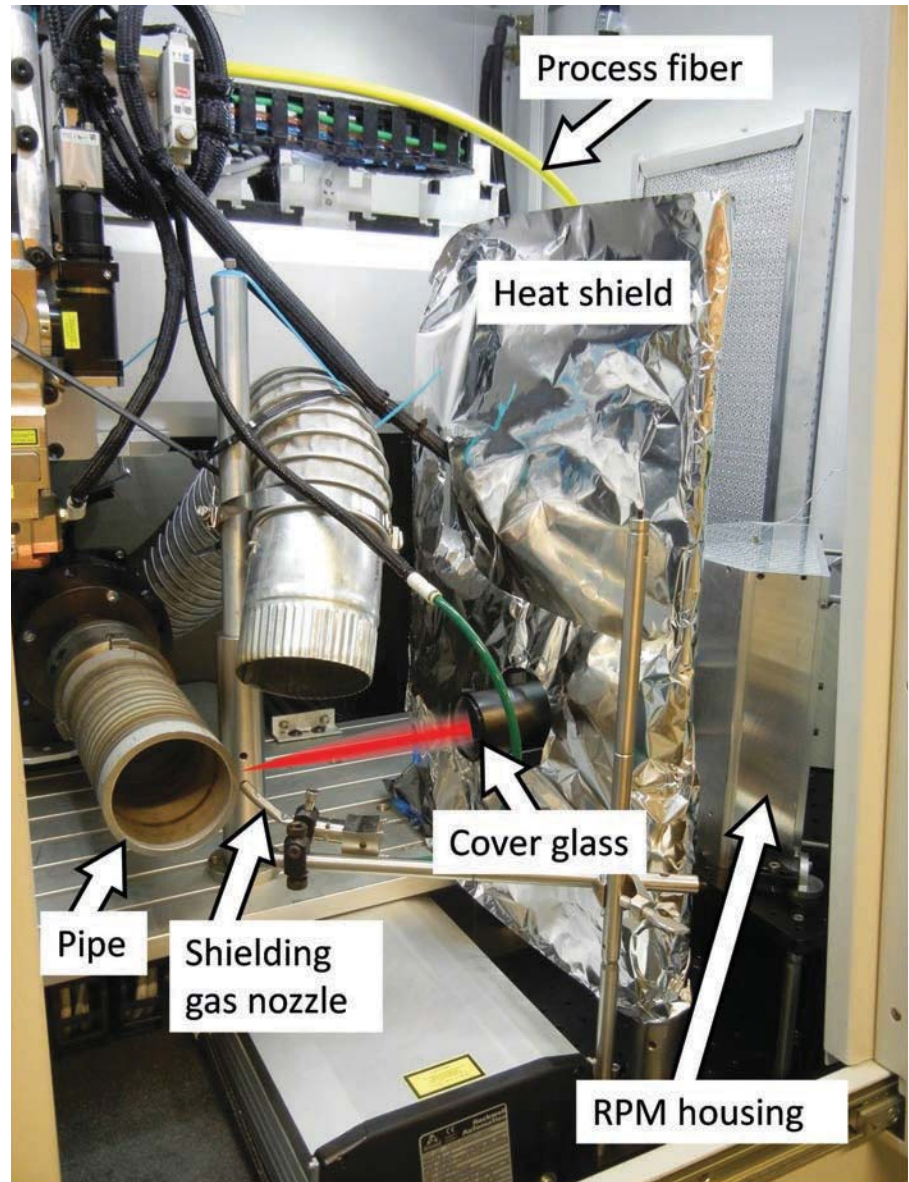


Fig. 3 — Radiation pressure power meter (RPM) in welding workstation. The focused laser light exits the cover glass (false-colored red beam) and is focused onto the workpiece (pipe).

recording the light force (radiation pressure), we measure the optical power of a laser beam. For perspective, 10 W of laser light causes a force of 66.7 nN (nanoNewtons), which is roughly the weight of an eyelash, 1 kW of light pushes with 6.67 μN (about the weight of a grain of sand), and 100 kW generates a force equal to the weight of about two staples (667 μN).

The prototype radiation pressure power meter was added to our welding workstation as shown schematically (an overhead view) in Fig. 2 and with a photograph of its implementation in Fig. 3. Because our current prototype was designed for a horizontally travelling laser beam, we modified the weld-

ing setup by removing the light delivery (“process”) fiber from the vertically positioned weld head and used an optical collimator to establish a collimated laser beam (all of the light travelling in an essentially parallel direction). This beam was reflected from the sensing mirror in our RPM and then was focused by a lens onto the workpiece.

Of course, accurate scales are notorious for their difficulty in operating in a vibrating environment, in the presence of air currents, or if their temperature is changing significantly. Inside a laser welding workstation, all three of these can be a problem. The scale was mounted to the inner floor

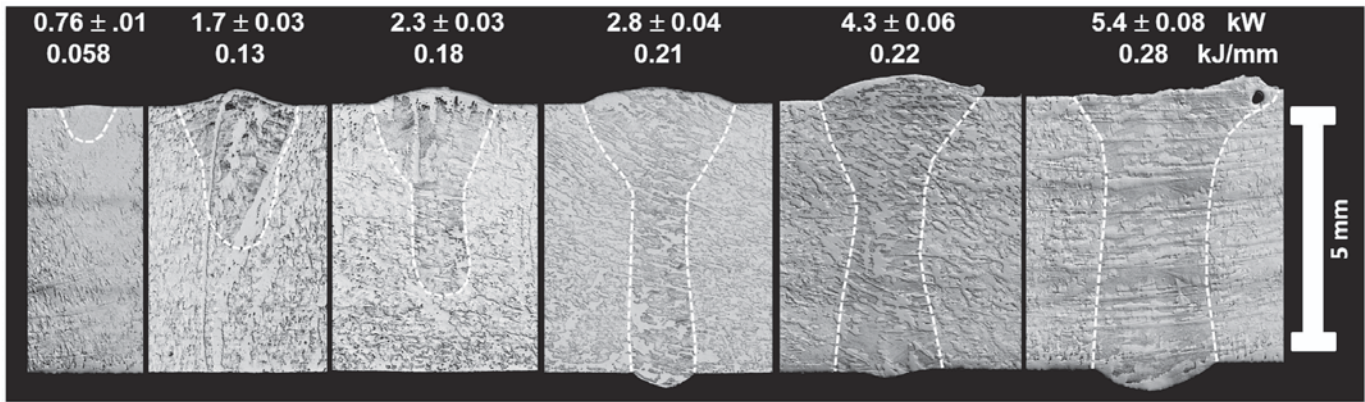


Fig. 4 — Macroscopic cross-sections of laser welds made on Type 304L stainless steel pipe during radiation pressure experiments. Real time, RPM-measured laser welding power (kW) and linear heat input HI (kJ/mm) are shown for each weld.

(a granite slab) of the welding workstation so it did not move with the translation stage on which the workpiece was mounted. The scale was protected by an aluminum housing (Fig. 2) with an anodized aluminum tube containing the focusing lens and a disposable cover glass to protect the lens from damage by weld splatter. Finally, the workpiece was placed at the focus of the laser light, ~300 mm from the lens. Nitrogen shielding gas was delivered from a nozzle placed approximately 2 cm from the workpiece. We found that heat from the weld pool and plume affected the scale's measurement, so a foil heat shield was placed between the weld location and the scale housing with a hole for the light to pass through. Of course, this setup is not typical for laser welding operations, but it allows us to test the performance of our prototype RPM. Further developments will be needed to miniaturize it to reside in the laser weld head itself and to implement noise rejection techniques allowing operation in a high-vibration environment.

Demonstration of Real-Time Radiation Pressure Technique

To demonstrate real-time laser-power measurement during the welding process, we performed several circumferential welds on a Type 304L stainless steel pipe of 89.5 mm outer diameter and a wall thickness of 5.6 mm. Nitrogen shielding gas was used to provide an inert environment and the beam was focused to a spot size of ~0.6 mm diameter at the workpiece. Travel speed (pipe rotational

speed) was increased with increasing laser power to maintain good weld quality based on visual surface inspection. After welding, the pipe was cross-sectioned, polished, and etched with mixed acid (equal parts HCl, HNO₃, and acetic acid) to reveal the macrostructure using optical microscopy. Figure 4 shows the cross-sections, which reveal weld penetration depth as a function of laser power as measured during the weld using the RPM. As expected, the weld penetration depth and total melt volume increased with laser power, reaching complete joint penetration at 2.8 kW beam power. Note that the linear heat input, *HI*, was calculated for each weld since pipe rotational speed ω (in units of mm/s) varied according to the selected laser beam power, *P*, so that $HI = P/\omega$.

The uncertainty of the laser power measurement using the radiation pressure power meter is a preliminary estimate and will be refined further with more measurements. But currently, the uncertainty is dominated by the uncertainty in our calibration of the scale over the lowest mass ranges (300–500 μg), which correspond to about 600–1000 W of laser power. We estimate that the uncertainty of the scale calibration at these lowest levels is about 1.5%. For now, we use this as our power uncertainty estimate. We are also aware of a potential thermal drift in the scale reading as higher powers or longer weld times change the temperature of the RPM. These effects must be addressed, but for the parameters measured here, any drift was simply removed by a linear approximation and we assigned a tentative laser power measurement uncertainty of 1.5%, which includes a coverage factor of 2 (sometimes referred to

as a “2 sigma uncertainty”) indicating that we expect the actual power has a 95% probability that it is within 1.5% of the value measured by the RPM.

Hybrid Power Measurement Technique to Achieve Accuracy and Speed

As mentioned, radiation pressure is a unique way to measure laser power because all other methods require the laser light to be absorbed. Traditionally, the tradeoff is between absorbing all the light for an accurate power measurement, or alternatively, measuring only a tiny “pick-off” fraction of the light allowing the rest of the light to be used for the welding operation. This second approach has lower potential accuracy but is a simple technique offering a fast way to see changes in laser power during a weld with a response time on the order of milliseconds or even microseconds. Current commercial scale technology, on the other hand, is not designed for such rapid measurements and as a result, our RPM has an approximate 5-s response time. In the short term, a hybrid approach between a radiation pressure power meter and a pickoff power monitor might be a solution to enable both rapid and accurate real-time measurements of welding laser power.

The pickoff approach is somewhat common and came installed in the fiber laser feeding our welding operation. In the measurement, a small fraction of the laser's light is absorbed for measurement using a photodiode (a small, semiconductor-based optical power detector). This device works like a small solar cell where light is ab-

sorbed by the photodiode and generates an electrical signal, which becomes a measurement of the incoming laser power. This gives a fast, real-time way to monitor the power from the laser. Since these delicate photodiodes cannot survive laser powers of more than a few milliwatts, they cannot measure the full laser beam. During laser operation, a very tiny fraction of the laser's light is diverted to the photodiode. The power measured by the photodiode is proportional to the total power in the laser, but that proportion is difficult to quantify because the ratio of diverted light to the total laser power (the "pickoff ratio") is so small. For example, if a photodiode capable of measuring up to 10 mW of optical power were used to measure a 1-kW laser, only 1/100,000 of the laser's power would be directed onto the photodiode. If we wanted merely a 10% uncertainty in the estimate of total laser power, we would need to know the power in the pick-off beam to a staggering 0.0001% of the total laser power. Thus, while the pickoff approach provides a fast and real-time measurement of laser power, its lack of calibration makes it poorly suited to high-accuracy power measurements.

Welding power measurements by means of the present force-balance technology, however, are also not ideal due to the limited response time. Figure 5 shows an example of the laser power measured during a circumferential weld done on the stainless steel pipe with the setup described previously. The laser power was stepped up halfway through the weld. The figure shows both a power measurement

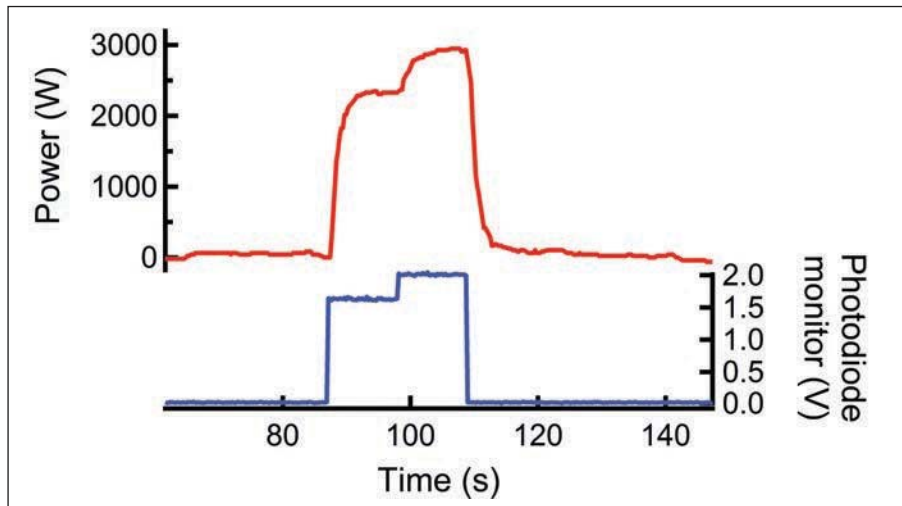


Fig. 5 — Plot of optical power measured with the radiation-pressure power meter (red, upper curve) and the uncalibrated photodiode pickoff monitor voltage (blue, lower curve).

from the RPM and the voltage from an uncalibrated photodiode. Clearly, the radiation pressure result is important because it measures accurate laser power, but the 5-s rise time (seen by the rounded corners on the rising edges of the RPM plot in Fig. 5) limits its ability to measure any changes in laser power that might occur on a timescale faster than a couple of seconds. This illustrates the continued usefulness of the pick-off power monitor as a fast measurement. We are considering potential improvements of the measurement speed of the scale. In the interim, perhaps the best result will be a hybrid where the radiation pressure power meter calibrates the photodiode in real time (eliminating concerns about drift in the pickoff ratio) to provide a fast and accurate measurement.

Conclusion

The results shown here demonstrate that a radiation-pressure-based approach of measuring the power output of a welding laser based on its push rather than the heat it generates is an exciting prospect. We showed that this technique can be used in a welding environment to achieve accurate real-time laser power measurements during a complete-joint-penetration weld. This radiation pressure technique provides accuracies and response times that meet or exceed the best specifications for thermal power meters but with the advantage of real-time measurement during a laser weld. Future development work will consider how to improve the response time through scale technology or in conjunction with other techniques (e.g., photodiode pickoff). [WJ](#)

Acknowledgment

The authors thank A. Feldman for his work developing the Distributed Bragg Mirror.

Note

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