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W. Small IV, P. M. Celliers,
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Two-Color Mid-Infrared Thermometer Using a Hollow Glass Optical Fiber

W. Small IV, P.M. Celliers, L.B. Da Silva, and D.L. Matthews

Medical Photonics Laboratory
Lawrence Livermore National Laboratory

ABSTRACT

A non-invasive two-color infrared thermometer has been developed for low-temperature biomedical applications. Mid-infrared radiation from the target is collected via a single 700 μm-bore hollow glass optical fiber, simultaneously split into two paths and modulated by a gold-coated reflective optical chopper, and focused onto two thermoelectrically-cooled HgCdZnTe photoconductors (bandpasses of 2-6 μm and 2-12 μm, respectively) by gold-coated spherical mirrors. The small numerical aperture of the hollow glass fiber provides high spatial resolution (<1 mm), and the hollow bore eliminates reflective losses. The modulated detector signals are recovered using lock-in amplification, permitting measurement of small low-temperature signals buried in the background. A computer algorithm calculates the true temperature and emissivity of the target in real time based on a previous blackbody (emissivity equal to 1) calibration, taking into account reflection of the ambient radiation field from the target surface.

As a result of the use of two measurement bands, dynamic temperature measurements of a target with unknown or changing emissivity can be made. Because the radiation observed through both bands originates from the same geometric region on the target (which may not be true when a separate fiber is used to collect radiation for each band), the calculated temperature and emissivity are independent of the fiber-to-target distance. This feature, together with the narrow acceptance cone of the hollow glass fiber, enables the user to alter the distance from the target without significantly sacrificing spatial resolution or accuracy.

This device is currently being used for laser tissue welding research. Specifically, it provides a means for assessment of the thermal dependence of the fusion mechanism. It has been incorporated into a feedback loop to control laser energy delivery and maintain a constant temperature at the weld site for an *in vivo* animal study, in addition to being used in numerous *in vitro* experiments.

1. INTRODUCTION

Radiation thermometry is a common non-contact method of measuring surface temperature. In particular, two-color pyrometry compensates for unknown or changing emissivity, which can vary with temperature and surface quality. Two-color pyrometers sample the the target radiance in two different spectral bands and infer the true temperature and emissivity using various algorithms. The spectral characteristics of the optical components and the detection sensitivity determine the useful temperature range of any radiation thermometer.

We have constructed a two-color mid-infrared thermometer using a single hollow glass optical fiber and lock-in amplification for fast, high spatial resolution, low-temperature measurement. Because the radiation observed through both bands originates from the same region on the target (which may not be true when a separate fiber is used for each band), the calculated temperature and emissivity are independent of the fiber-to-target distance. This feature, together with the narrow acceptance cone (small numerical aperture) of the hollow glass fiber, enables the user to alter the distance from the target without sacrificing spatial resolution or accuracy.

2. THEORY

The spectral radiant emittance of a blackbody (emissivity equal to 1) is given by Planck's Law:

$$W_{\mathrm{bb}}(\lambda, T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1} \tag{1}$$

where h is Planck's constant, c is the speed of light, λ is the wavelength, k is Boltzmann's constant, and T is the blackbody temperature [K]. The emission peaks of low-temperature (300-500 K) radiation fields are situated in the mid-infrared around 7 μm (higher temperatures peak at shorter wavelengths).

Assuming the fiber-to-target distance is large compared to the fiber radius (or bore radius, in the case of a hollow fiber) and radius of the sensed area, the signal yielded by a detector using an optical fiber to collect the blackbody radiation is

$$V_{\mathrm{bb}}(T) = \pi a_{\mathrm{f}}^2 \mathrm{NA}^2 \int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} d\lambda W_{\mathrm{bb}}(\lambda, T) F(\lambda) S(\lambda) \tag{2}$$

where NA is the numerical aperture of the fiber, a_{f} is the fiber (bore) radius, $F(\lambda)$ is the fiber transmittance, and $S(\lambda)$ is the detector response. The detected signal is independent of the fiber-to-target distance.

For a graybody (emissivity less than 1 and independent of wavelength), the spectral radiant emittance becomes

$$W(\lambda, \varepsilon, T) = \varepsilon W_{\mathrm{bb}}(\lambda, T) \tag{3}$$

where ε is the emissivity. In this case, the ambient radiation filed will be reflected from the target surface and contribute to the detected signal:

$$V(\varepsilon, T_{\mathrm{targ}}) = \varepsilon V_{\mathrm{bb}}(T_{\mathrm{targ}}) + (1-\varepsilon) V_{\mathrm{bb}}(T_{\mathrm{bg}}) \tag{4}$$

where T_{targ} is the target temperature and T_{bg} is the known ambient background temperature near the target. The first term represents the contribution from the target and the second term represents the contribution from the reflected ambient (blackbody) radiation field. Using two detectors of different spectral bandpass yields two such equations, enabling solution for the two unknowns, target temperature and emissivity.

3. DEVICE CONFIGURATION

The configuration of the optical components is shown in Figure 1. Radiation emitted by the target is collected by a single hollow glass fiber and transmitted to a reflective optical chopper to modulate the incident radiation for lock-in amplification while simultaneously splitting the radiation into two paths. Two gold-coated spherical mirrors focus the radiation onto their corresponding thermoelectrically-cooled photoconductors. The spectral bandpasses of the photoconductors are 2-6 μm and 2-12 μm and their response times are 100 ns and 10 ns, respectively. The two signals recovered using lock-in amplification are sent to a computer to calculate the temperature and emissivity based on previously obtained blackbody calibration equations.

4. NUMERICAL APERTURE AND SPATIAL RESOLUTION

The acceptance cone of the hollow glass fiber was determined experimentally by scanning the fiber across an interface between black anodized and white spray painted aluminum at several fiber-to-target distances and recording the voltage signal from the 2-6 μm detector. Because the two surface types have different emissivities, the signal gradually changed across the interface. For each scan, a gaussian radial acceptance function was calculated. Plotting the 1/e half-width of each gaussian (i.e., the radius of the area on the target sensed by the fiber) versus the corresponding fiber-to-target distance (Figure 2) shows that the acceptance cone half-angle of the fiber is only about 2° (numerical aperture of about 0.04), providing high spatial resolution (~1 mm for fiber-to-target distances within 2 cm).

5. CALIBRATION AND CALCULATION

The system was calibrated by measuring the signal of each spectral band as a function of the target temperature using a blackbody target. The blackbody was a 10 x 10 x 10 cm aluminum block with a 4 x 4 x 4 cm hollow cavity in the center. A thermocouple was placed within the aluminum wall to measure the actual blackbody temperature. The fiber was inserted into a bore in the aluminum wall such that the fiber tip was flush with the cavity edge. Figure 3 shows the calibration compared to theory (Equation 2). The curves were fit using an exponential function:

$$V_{\mathrm{bb}}(T) = \exp\left(a + \frac{b}{T} + cT\right) \tag{5}$$

where the fit parameter a is a scaling factor and b and c are governed by the spectral (temperature) response of the each detector.

Substituting the experimentally determined blackbody temperature response (Equation 5) into Equation 4 yields two equations (one for each spectral band) which can be solved simultaneously for the target temperature and emissivity. However, when the target temperature is equal to the ambient background (i.e., when the target is in thermal equilibrium with its surroundings), no emissivity information is available.

6. SAMPLE MEASUREMENTS

Figure 4 shows the two-color temperature and emissivity as a function of fiber-to-target distance from a uniformly heated target. The values are independent of the fiber-to-target distance, which agrees with theory.

Porcine skin coated with a thin layer of indocyanine green dye (ICG) was irradiated with a pulsed 805 nm diode laser at about 2 W (spot diameter = 4 mm). The measured two-color temperature and emissivity histories at the center of the laser spot (spatial resolution ≈ 1 mm) for two different sub-second pulse widths are shown in Figure 5.

7. SUMMARY OF KEY FEATURES

The hollow glass optical fiber-based two-color mid-infrared thermometer enables non-contact, fast, high spatial resolution temperature and emissivity measurement. The mid-infrared bandpasses of the fiber and detectors, coupled with lock-in amplification, permit low-temperature measurement. As a result of the two-color principle, the true temperature and emissivity are determined (assuming the emissivity is independent of wavelength within the measurement band).

Use of a single fiber eliminates the problem of aligning two fibers to a common spot on the target. Because the radiation observed through both bands originates from the same region on the target (which may not be true when a separate fiber is used to collect radiation for each band), the calculated temperature and emissivity are independent of the fiber-to-target distance (for a target of uniform temperature over the observed surface area). This feature allows the user to dynamically adjust the distance between the fiber tip and the target. The hollow glass fiber has a small numerical aperture (~1 mm spatial resolution), is flexible, and, unlike silver halide mid-infrared transmitting fiber, does not degrade under room lights.

ACKNOWLEDGMENTS

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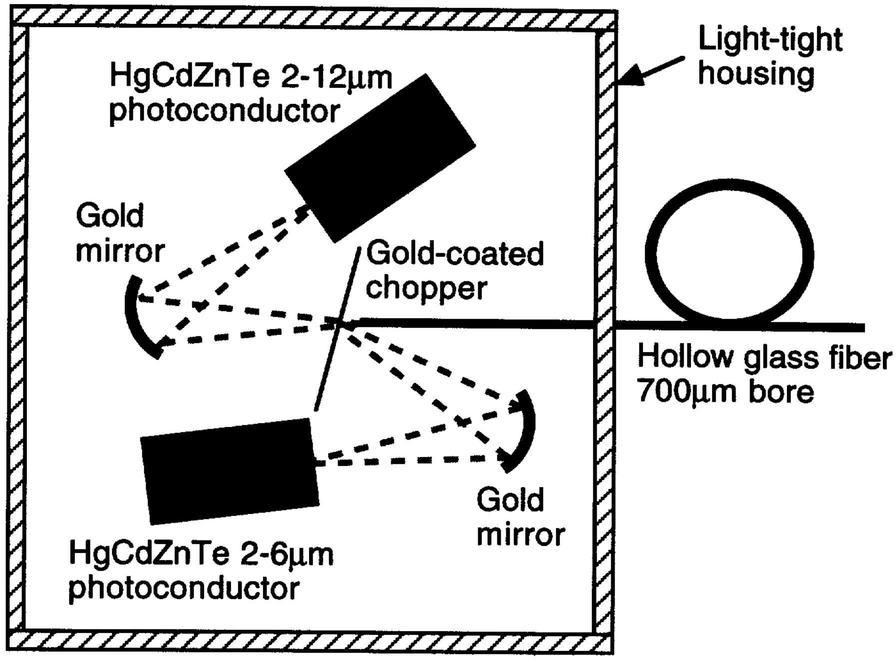

FIG. 1. Configuration of the optics in the two-color mid-infrared thermometer. The radiation transmitted by the fiber is either passed or reflected by the chopper, simultaneously modulating the radiation for lock-in amplification and splitting the radiation into two detection paths. Each detector samples the radiation in a different spectral band, providing two signals--each of which is dependent on the target temperature and emissivity.

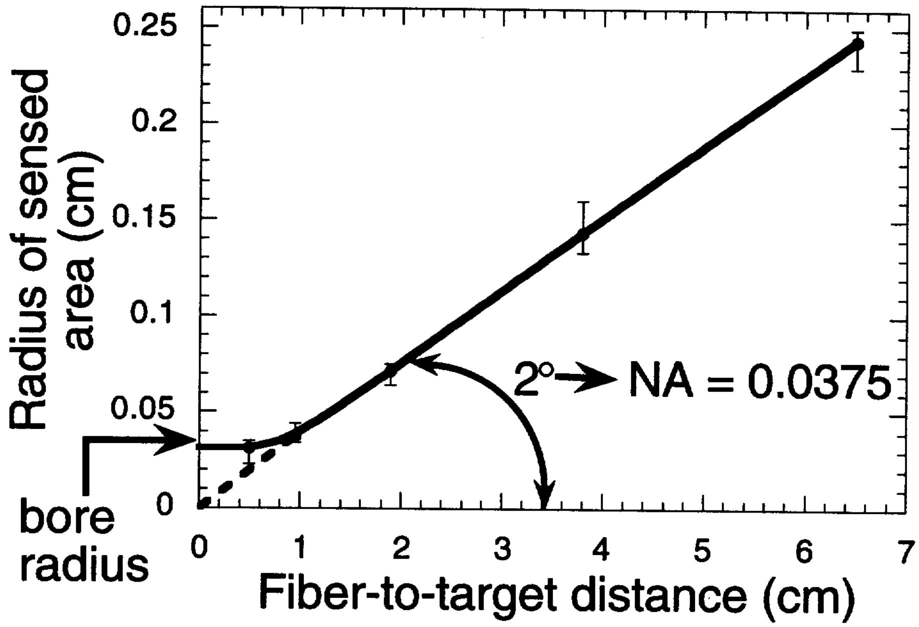

FIG. 2. Radial acceptance cone of the hollow glass fiber. As the fiber-to-target distance approaches zero, the radius of the sensed area approaches the bore radius. For fiber-to-target distances less than 2 cm, the spatial resolution is around 1 mm.

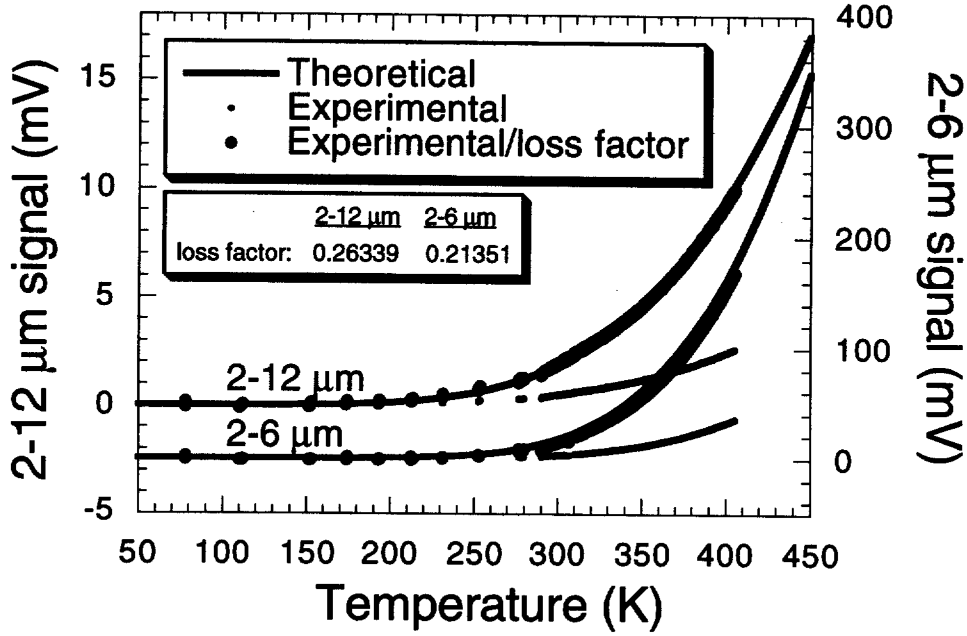

FIG. 3. Experimental and theoretical blackbody calibration curves. Division of each experimental curve by a constant representing coupling losses shows that the experimentally determined calibration equations agree with those derived theoretically. The major coupling losses arise from the astigmatism caused by the large angle of incidence of the light on the mirrors and transmission losses in the hollow glass fiber. The experimental calibrations are used to calculate the temperature and emissivity of any graybody target.

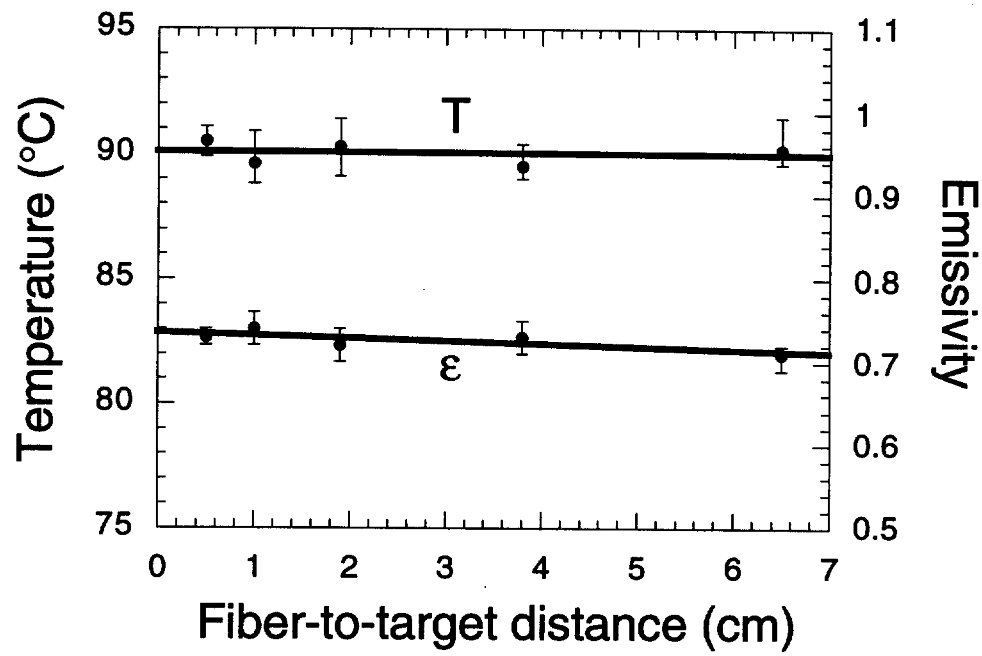

FIG. 4. Two-color temperature and emissivity versus fiber-to-target distance from a uniformly heated surface (hot plate) at constant temperature. The data points represent average values and the error bars represent minimum and maximum values over a 5 s interval. Both temperature and emissivity are independent of the fiber-to-target distance.

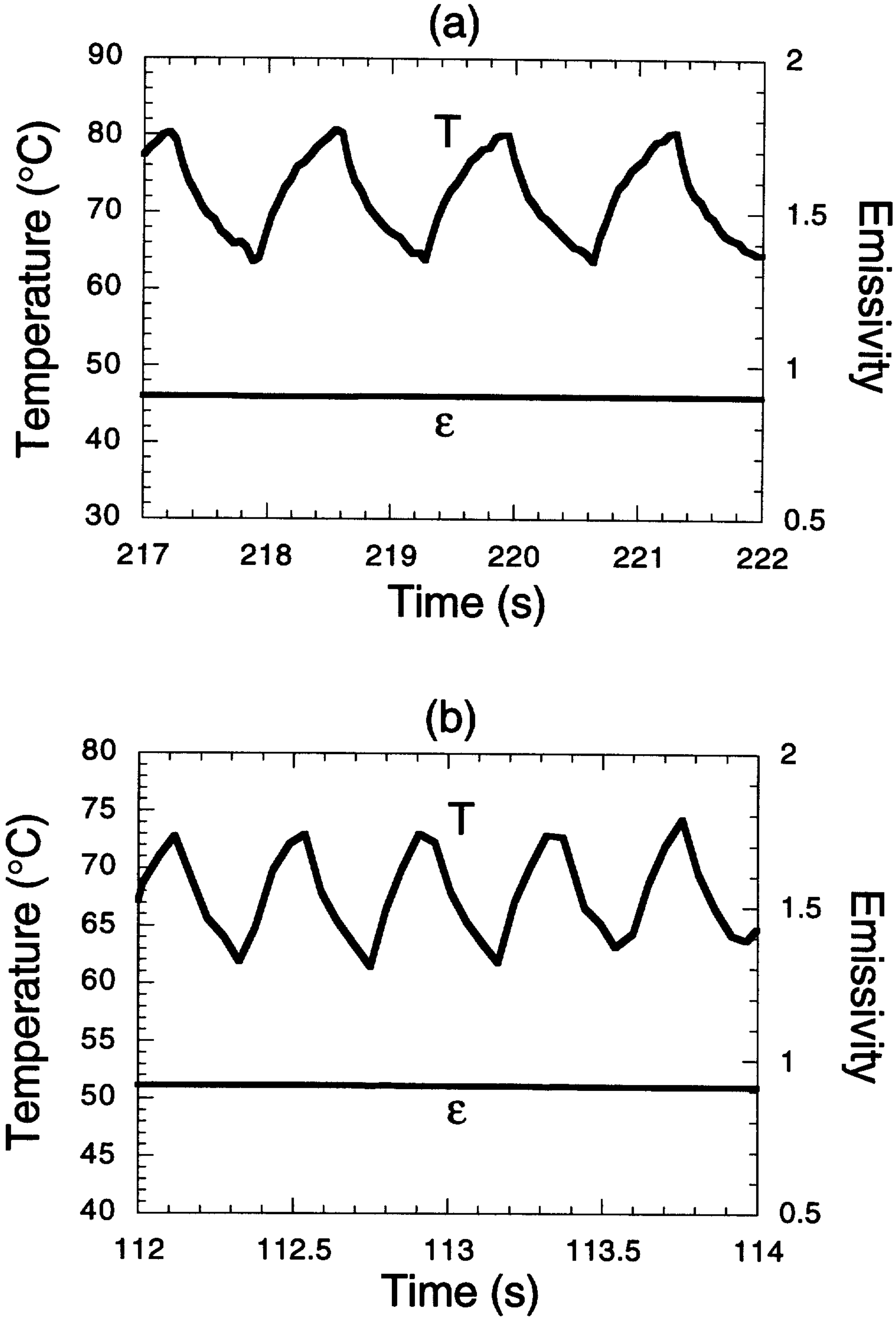

FIG. 5. Two-color temperature and emissivity histories for ICG-coated porcine skin heated with an 805 nm diode laser using (a) ≈700 ms pulses and (b) ≈200 ms pulses. Measurements were taken at a rate of 20 Hz. Sub-second temperature changes were easily resolved.

Technical Information Department **• Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551