Novel millimeter wave sensor concepts for energy, environment, and national security

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Novel Millimeter Wave Sensor Concepts for Energy, Environment, and National Security

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Abstract—Millimeter waves are ideally suited for sensing and diagnosing materials, devices, and processes that are broadly important to energy, environment, and national security. Thermal return reflection (TRR) techniques that detect and use thermal emission as a probe to diagnose materials and systems make possible accurate noncontact thermal analysis measurements that can resolve emissivity and temperature simultaneously. Scientific basis of TRR, 2-D and potentially 3-D measurements, and applications of TRR are discussed.

I. INTRODUCTION AND BACKGROUND

Millimeter wavelengths provide a unique capability for in situ thermal analysis of materials by being long enough to penetrate dust, smoke, and otherwise optically obscure propagation paths and materials yet short enough to enable focusing and manipulating of the signals for spatially resolved applications. Thermal emission signals from a material or surface are proportional to the product of the emissivity and temperature (εT) of the material or surface that is viewed. The emissivity is related to material phase state, chemistry, and molecular structural characteristics such as corrosion and creep that typically depend on temperature. Methods that can resolve the emissivity and temperature are of general interest to thermal analysis, particularly at high temperatures when pushing the limits of material applications. An active millimeter-wave pyrometer that can measure emissivity along with temperature has been demonstrated. The main limitation of that approach was that the leaked local oscillator signal used to probe the viewed emissivity was coherent. Therefore, a standing-wave interference effect in the measurement setup had to be accounted for. We have demonstrated that incoherent thermal emission from the viewed sample can be redirected back to the sample and used to probe its emissivity, and consequently, resolve the parameters of the thermal emission product εT without standing wave uncertainties. The analytical basis has been derived for determining these parameters using the thermal return reflection (TRR) method.

II. ANALYTICAL BASIS

The previously derived TRR method has been extended to allow for non opaque specimens as shown in Figure 1. The receiver views a specimen (S) through a beamsplitter (BS) and waveguide system (WG). The specimen thermal emission is used as a probe from the front and behind by mirrors TRR M and SRR M, respectively. The analysis requires taking into account all of the sources and losses of signal in the field of view of the receiver. Each component has associated with it an emissivity (ε), temperature (T), transmission factor (τ), and reflectivity (r). The analysis now allows for a non opaque specimen with a single pass transmission factor of τs. If a component is at room temperature, then its emissivity and temperature will cancel out as in the case of the beamsplitter. The analytical results for the measured temperature at the receiver for the various thermal probing cases are given by:

\[ T_{eff} = \tau_w \varepsilon_s T_s + \varepsilon_w T_w + r_s \tau_w \varepsilon_w T_w \]  \hspace{1cm} (1)

\[ T_{eff}^s = \frac{T_{eff}}{1 - \tau_s \tau_w \varepsilon_w^2} \]  \hspace{1cm} (2)

\[ T_{eff}' = \frac{T_{eff}}{1 - \tau_s \tau_w \varepsilon_w^2} \]  \hspace{1cm} (3)

where \( T_{eff} \), \( T_{eff}^s \), and \( T_{eff}' \) are the MMW temperatures measured at the receiver without any thermal feedback, with only feedback by SRR M, and with only TRR M reflection, respectively. \( T_w \) and \( T_s \) are the waveguide and specimen temperatures, \( \varepsilon_w \) and \( \tau_w \) are the waveguide emissivity and transmission related by \( \varepsilon_w = (1 - \tau_w) \), \( \varepsilon_s \), \( \tau_s \), and \( r_s \) are the emissivity, transmission, and reflectivity of the specimen where in the limit for a completely opaque specimen \( \varepsilon_s = (1 - r_s) \), \( r_{bs} \) is the beamsplitter reflectivity and \( \tau_s \) is the return emission coupling factor taking into account reflected field of view divergence and alignment. A fourth equation is obtained for simultaneous reflection by both mirrors by replacing \( T_{eff} \) in Eq. 3 by \( T_{eff}' \). For a specimen that is not completely opaque or transparent the emissivity depends on both the specimen absorption and reflectivity. The set of four equations makes possible the determination of the specimen temperature, emissivity, and coupling factor where the emissivity depends on both the specimen bulk absorption and surface reflectivity. These parameters are resolved for the direction of view and for the polarization of the receiver system. Using the layout illustrated in Figure 1 as a building block additional spatial and polarization dimensions can be added to study specimens with...
complex anisotropic geometries. Multiple receivers could also be added to one dimension with different fixed thermal probing configurations for real time fast transient analysis of the specimen behavior under controlled changing environmental conditions such as temperature, atmosphere, or stress.

III. DISCUSSION

We extend our approach to 3-D measurements. The emissivity ($e$), temperature ($T$), and transmission factor ($r$) of waveguides for $X$, $Y$, and $Z$ directions can be used and reflectivity ($r$) can be determined following the three directions (Figure 2). Losses due to each waveguide and other components can be corrected so that three respective receivers measure the true transmission along each direction. Though three identical optics and receiver systems could be fabricated and used, TRR will be used to calibrate and correct for losses or any alignment errors. This approach can be used in two different modes: 1) directly viewing from three-different directions (3-D viewing) and 2) splitting the signal three ways using 3-D optics to track three different properties or parameters (3-D signaling). Equation 3 can be rewritten for 3-D application, e.g., for a simple case of only TRR M reflection:

$$T_{3D} = \frac{T_{eff}}{1 - r_x^2 r_y^2 r_z^2} + \frac{T_{eff}}{1 - r_x^2 r_y^2 r_z^2} + \frac{T_{eff}}{1 - r_x^2 r_y^2 r_z^2} \tag{4}$$

More detailed analytical solutions for specific applications can be derived as shown in [2].

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure2.png}
  \caption{Conceptual scheme of 3-D measurements}
\end{figure}

Also new sensor concepts are possible based on emit-probe and pump-probe modes to further broaden its applications. In its 3-D manifestation of this technique, one can track three different parameters or view/measure at three different directions ($x$, $y$, and $z$). This shows promise for measuring temperature ($T$) - position ($x$) - time ($t$) simultaneously in real time leading to T-x-t diagrams that can be exploited for spatial resolution of emissivity or stability over a function of time. The 3-D manifestation can be implemented by simply connecting three MMW receivers pointed at the sample from $x$, $y$, and $z$ directions for 3-D viewing. Alternatively, 3-way splitter can be designed and implemented.

New materials sensor technologies are needed for energy, environment, and national security applications For example, the development of Generation IV very high temperature nuclear energy reactor (VHTR) technology depends on the development and characterization of high temperature anisotropic graphite and alloy materials that can reliably meet the diverse fuel and structural requirements in extreme environments. The thermal dynamics and properties of anisotropic ceramic composite, carbon fiber-reinforced carbon (C/C) and SiCf/SiC materials of relevance to VHTR technology are not well known using orthogonally polarized dual beam MMW measurements.

In the case of environment application, we have demonstrated 2-D temperature distribution of cold cap in a joule-heated melter used for melting of simulated nuclear waste glass melting (vitrification) [3]. This can potentially be extended to 3-D measurement to track emissivity/temperature changes in the plenum or inside the bulk material or melt.  

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{figure3.png}
  \caption{2-D Temperature profile inside the melter [3]}
\end{figure}

Emissivity of moving body or material or gas space can be tracked for national security applications. These can be translated into 3-D temperature, which will be valuable for detecting moving targets, strange movements, and hidden objects. By incorporating time delay in one or more of the directions, one can capture situational dynamics in real time. These data can potentially be fused with MMW imaging technologies to confirm and validate data or information critical to intelligence community.

REFERENCES