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Simulating radiation thermometer temperature measurement error from the performance change of an interference filter due to polarization effect

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ABSTRACT

A radiation thermometer is an optical instrument in which the dielectric optical filter is a critical component. Dielectric multilayer optical filters are favored in most radiation thermometer designs for selecting a certain wavelength range of the flux. As a component those filters are affected by different conditions to which they are exposed, which might lead to error in temperature measurement using radiation thermometer. The radiation thermometer is mostly used at normal to the flux source where the interference filter have the possibility of receiving collimated radiant flux (angle of incidence 0°) after passing through a lens, but there are optical set up situation where the lens involved converge part of the flux beam. In a converged beam the incidence angle can be within a range of approximately 0–20°. In this situation the measured temperature will be affected, as polarization introduces some error specifically from the interference filter. The error might be very small for most industrial applications, but quantifying it is beneficial specifically for high accuracy measurement required in high temperature measurement. It will be demonstrated through simulation how the polarization effect can be quantified and be related to temperature error by considering different design conditions of a multilayer interference filter. The paper also demonstrates how a polarization consideration in a multilayer dielectric filter design can minimize this error. It is practically demonstrated that wavelength shift, broadening of a full width at half maximum (FWHM) and reduced transmittance at central wavelength can be determined by comparing the performance of the designed optical filters.

1. Introduction

A radiation thermometer is an instrument that is used to measure temperature without contacting the source. Determination of temperature using a radiation thermometer requires a thorough understanding of the different optical components' behavior. One such component is a dielectric optical multilayer interference filter. Interference filters are used to select a suitable wavelength range from the radiant flux that is received. For high temperature measurement narrow-band interference filters are favored, as corrections and errors can be minimized, but at the same time the range is wide enough to allow enough radiant flux into the detector. Apart from this, the wavelength range needs to be selected based on an estimation of the surrounding atmospheric conditions and temperature range of the required measurement. This is a challenge that needs to be addressed when selecting the wavelength range [1]. Interference filter wavelength selection capability is dependent on the surrounding temperature and polarization effect. The polarization effect can lead to error in temperature measurement owing to its effect on the shifting of the central wavelength [1,2–5]. Radiation thermometers can usually be calibrated as a system in order to eliminate the need for calibrating each component separately. The paper will take on a challenge to study the polarization effect on a radiation thermometer by relating it to a polarization effect on one of its components, the interference filter, and approximately determine the corresponding temperature error.

This study investigates the phenomenon that the polarization effect on the optical interference filter can cause radiation thermometer temperature measurement error when the flux incidence angle increases. It is also discussed that consideration of the polarization effect in the design phase of the interference filter can minimize the polarization effect when the incidence angle increases. The theoretical background of the interference filter and the associated polarization effect is discussed in the theory section, while the methodology employed to demonstrate the polarization effect will be discussed in the methodology section. The section on the results and discussion part will deal with the results before concluding remarks are offered in the last section.

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2. Theory

The polarization effect on interference filters (designed for normal incidence) originates from the effect of viewing the radiant flux at an angle other than normal. A dielectric interference filter can have a number of very thin layers whose spectral performance can easily change in response to the change in incidence angle. This individual performance change can lead to an overall radiant flux transmission performance change. Specially designed interference filters can also be prepared so that the polarization effect can be minimized, thus minimizing the effect on the transmitted radiant flux.

2.1. Optical multilayer stack

A multilayer stacked dielectric interference thin film filter is a structure in which a number of carefully designed nano/micro-layers are deposited one on top of the other on an appropriate substrate (see Fig. 1). This kind of structure does have the designed capability to select a certain wavelength range of incidence flux. Each layer can be designed so that the optical filter has a particular interference capability. The thin film layers can be fabricated from two or three materials alternately deposited one on top of the other. The interference capability of each layer can be represented mathematically by a 2 × 2 transfer matrix that includes the refractive index of the material, physical thickness and incidence angle of the flux within each thin layer. The overall transmission performance of the stack can be represented by the multiple effect of each layer, together with the effect from the incidence and substrate medium. The theory is described well in [2–4].

When the flux is incident on the optical filter at a certain angle other that 0° the flux will be polarized in the S- and P-polarized mode. At angles greater than 0° the component of flux traveling parallel to the plane of incidence and reflection (P-plane) will be filtered differently than the component traveling perpendicularly to the plane of incidence (S-plane). A vertical vector, which is perpendicular to the multilayer structure, and propagation vector defines the geometry of the plane of incidence. The increase in the angle of incidence leads to an increase in the polarization effect.

The optical filter design needs to set allowance for the polarization effect if the flux reaches the optical filter at angles different from 0°. Usually a radiation thermometer is used at normal to the flux source and assuming 100% collimated flux arrives at the interference filter after passing through the lens set up the optical filter design may not need to consider polarization effect under the assumption that the effect is minimal or most commercially available optical filters are designed for normal incidence [1,5]. In a radiation thermometer optical set-up the optical filter is placed between the flux source and the detector, but mostly a collimating lens is placed in front of the optical filter (see Fig. 1). Part of the flux passing through the lens reaches the filter as a converging beam rather than collimated flux ranging from 0° to 20° due to the fact that the lens is flat but curved to the level that can create polarization effect. As a result the structure of the lens introduces a polarization effect as the beam reaches the filter in a range of angles. The set of flux beams arriving at the filter surface will be filtered differently because of the angle change effect. This could be the source of temperature measurement error. The error is caused partially by the shift of the central wavelength of the optical filter, the decrease of peak transmittance and broadening/narrowing of FWHM. Because of the decrease in the peak transmittance the amount of flux transmitted will decrease. Through the broadening of the FWHM, unwanted signal will be transmitted from outside the wavelength range of interest. Through the narrowing of the FWHM, a certain wavelength range of the flux will be blocked. The polarization effect on an interference filter can be approximated through Eq. (1) by considering the interference filter central wavelength shift [1]

$$\lambda_c = \lambda_o \frac{(n_*^2 - \sin^2\theta)1/2}{n_*}, \tag{1}$$

where:

λ_c – shifted interference filter central wavelength due to angle change
λ_o – central wavelength of the filter at design incidence angle
θ – incidence angle of radiant flux
n_* – interference filter effective refractive index which can be determined from the stack of thin layers of the multilayer optical filter.

The overall central wavelength shift consists of a shift mainly from polarization effect. Without considering the effect of other filters that will be added to remove the secondary transmission in the out-of-band region, the central wavelength shift from the polarization effect denoted as δ λ can be approximated by Eq. (2),

$$\delta\lambda = \lambda_c - \lambda_o, \tag{2}$$

$$A =_C \left[1 - 6\left(\frac{\sigma}{\lambda_C}\right)^2\right], \tag{3}$$

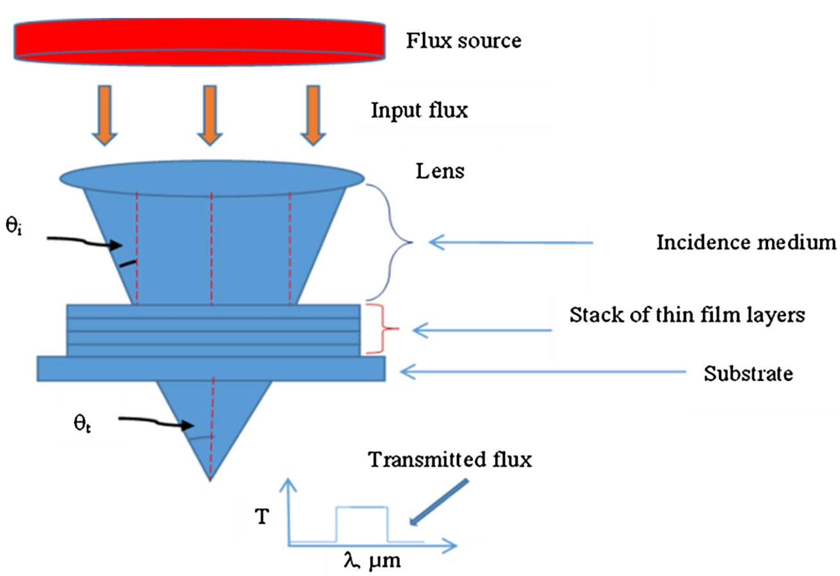

Fig. 1. A dielectric multilayer interference filter stack selecting the desired wavelength range of the input flux.