Phase-sensitive CMOS photo-circuit array for modulated thermoreflectance measurements

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A scalable 4×4 array of photodiodes and circuitry has been fabricated and used to make spatially resolved measurements of surface wave enhanced modulated thermoreflectance. In-phase and quadrature components of the modulated light at every pixel are measured in parallel, even in the presence of a large DC background.

Introduction: The optical reflectivity of many materials is temperature dependent. Thermoreflectance techniques exploit this phenomenon to sense surface temperature by measuring the reflected intensity of an optical probe beam. Coefficients of reflectivity are typically very low, usually less than 10^{-4}/K, but if the source of thermal energy can be mechanically chopped or otherwise modulated then narrowband, phase-sensitive detection techniques can be applied. Surface wave enhanced thermoreflectance benefits from deep and extremely narrow dips in the reflectivity caused by coupling of surface waves. If the angle between the surface and the probe beam is adjusted to be on the slope of one of these dips, there is a large amplification of any temperature induced changes in reflectivity [1].

Modulated thermoreflectance has generally been a point measurement technique, using a single photodetector to detect variations in the probe beam intensity. Since the thermal signals are converted to a time varying light signal it is difficult to visualise the spatial distribution of these quantities over a wide field. CCD cameras are not ideal for modulated measurements because the response speed is insufficient, and more importantly, because they have insufficient dynamic range to detect the small AC signals in a large, unwanted DC background. However, arrays of photodiodes combined with active and passive components can be fabricated using standard CMOS processes. These can be used as a cost-effective and flexible alternative to CCD imaging technology [2]. This approach has been adopted here to prototype a small but scalable array of 4×4 pixels which can simultaneously measure the spatially resolved amplitude and phase of the AC component of modulated light in the presence of a large DC background. This Letter describes the sensor and the results of applying it to surface wave enhanced modulated thermoreflectance measurements.

CMOS photo-circuit array: The sensor is fabricated in a 0.35 μ, 3.3 V process with three metal and two polysilicon layers (Austriamicrosystems CSI). It measures 1.75×1.75 mm and occupies one quarter of a larger die. The light sensitive, or focal plane region contains an array of 4×4 pixels measuring 200×200 μ each. The third metal layer is used to shield most of the sensor circuitry from unwanted light but parasitic photodiodes formed between *p*-substrate and *n*-well material are exposed to modulated light through windows cut in the metal shield. Light falling on the exposed diode generates a photocurrent. This subthreshold current is converted logarithmically to voltage by a series pair of diode-connected NMOS transistors (Fig. 1).

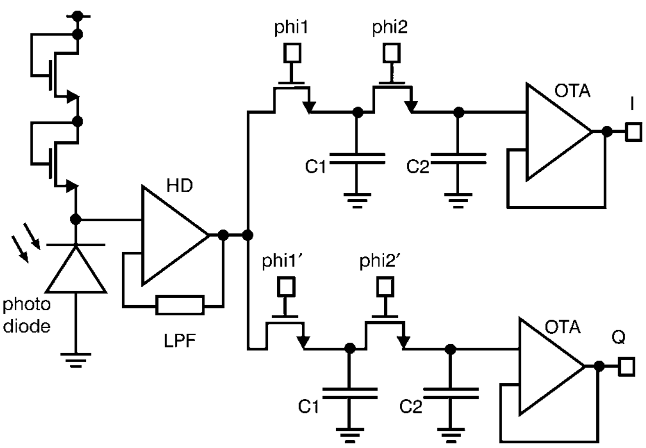

Fig. 1 *Circuitry in each array pixel*

The voltage is amplified and bandpass filtered by a hysteretic differentiator (HD) [2]. An HD is an operational transconductance amplifier (OTA) with a lowpass feedback network. For DC and low frequencies an HD acts as a voltage follower and the feedback maintains stable bias conditions. However, the OTA is effectively open loop at signal frequencies and voltage gain of 40 dB is typical. The low frequency cutoff is determined by the lowpass feedback network. The design used here can be switched between 1 or 10 kHz by changing an internal capacitance. The high frequency cutoff depends on the bias current of the OTA and is controlled by a single external resistor.

Phase sensitive detection is performed by a simple IQ demodulator. The demodulator I channel consists of switched capacitor C1 and integrating capacitor C2. The OTA buffers the output. Local oscillator (LO) phi1/phi2 is a pair of non-overlapping clocks at the signal modulation frequency. On the falling edge of phi1, the amplified and filtered signal waveform is sampled at a constant phase each cycle and held on C1. On phi2 these samples are integrated onto C2 with $C2 \gg C1$. Clocks phi1′ and phi2′ are delayed by 90° from phi1 and phi2 and together with C1′ and C2′ form the Q channel. Address decoders allow random access to the array and chip level buffers drive *I* and *Q* outputs off chip where, in our experiments, they are typically converted into an amplitude and phase value.

This mixer and integrator design is simple and very compact, especially for relatively low modulation frequencies where otherwise, prohibitively large time constants are needed. The amount of sample averaging and hence the detection bandwidth is determined by the ratio of C1 and C2. The main disadvantages compared to continuous time designs are the low speed caused by inefficient averaging (the mixer does not use the whole signal waveform) and the integration of all signal harmonics, both even and odd.

Experiment and results: Initially, the effect of varying the signal phase was investigated by illuminating the sensor with a sinusoidally modulated LED with an optical modulation depth of 1.5% while varying the phase of the LO clocks. Fig. 2 shows the measured amplitude and phase (calculated from I and Q) against the LO phase shift and demonstrates the phase sensitivity. The result in Fig. 2 was obtained 'single-shot' but we generally use averaging to reduce noise when using this prototype sensor.

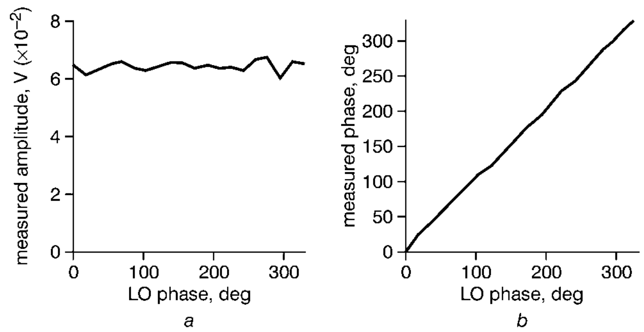

Fig. 2 *Measured amplitude and phase against LO phase shift*
a Amplitude
b Phase

For the modulated thermoreflectance measurements, the surface of interest was positioned in a corner-cube arrangement (Fig. 3), enabling the probe and imaging paths of the system to remain aligned while the surface is rotated to the vicinity of a surface wave reflectivity dip. The probe beam was provided by a collimated laser diode (650 nm, 5 mW). A focused pump beam (532 nm, 200 mW), mechanically chopped at 1 kHz, was used to induce a temperature change in the surface. To maximise sensitivity by accessing very sharp dips in reflectivity, the surface consisted of a 45 nm layer of gold covered with 400 nm of SiO_2 [3].

Any temperature rise induced by absorption of the pump beam energy causes a shift in the reflectivity dip. In this way, the pump laser was used to modulate the reflectivity of the surface, causing a subsequent modulation of the probe beam intensity. The thermally pumped region was imaged onto the CMOS photo-circuit array by lenses L1 and L2. An optical interference filter centred at the probe beam wavelength was used to exclude any stray pump light from the sensor. LO clock signals were synthesised from the chopper driver. To demonstrate the spatial resolution of the sensor, the focused pump beam was incrementally scanned across the surface such that the temperature rise was centred on different pixels in turn. A series of 4×4 pixel 'images' of probe beam modulation amplitude recorded at each pump beam position are shown in Fig. 4. A variation in signal strength at different pixels can be observed in Fig. 4, and is primarily due to the large range of photodiode sizes (between 8×8 and 60×60 μ) used to investigate performance trade-offs on this prototype device.

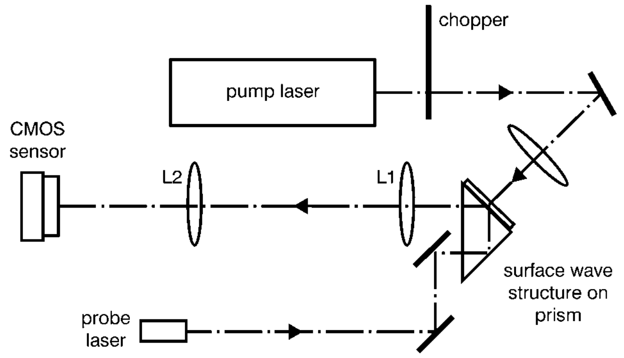

Fig. 3 *Experimental setup for modulated thermoreflectance experiment*

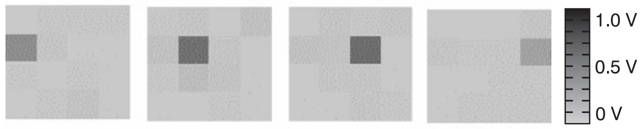

Fig. 4 *Series of spatially resolved modulated thermoreflectance measurements as pump beam is scanned across sample surface from left to right*

Conclusions: A small but scalable array has been fabricated and used to make spatially resolved measurements of surface wave enhanced modulated thermoreflectance. The frequency of modulation and low contrast make this a difficult measurement to perform with a CCD. A larger array with increased on-chip averaging is now being designed and will be used to perform further wide field thermoreflectance measurements. Other applications will include heterodyne microscopy, heterodyne electronic speckle pattern interferometry for displacement, vibrometry and ultrasound measurement and ultrasound modulated optical tomography.

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