

## The SKED: speckle knife edge detector

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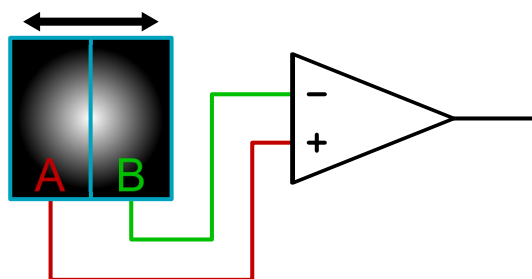
### **Abstract.**

The knife edge detector—also known as optical beam deflection—is a simple and robust method of detecting ultrasonic waves using a laser. It is particularly suitable for detection of high frequency surface acoustic waves as the response is proportional to variation of the local tilt of the surface. In the case of a specular reflection of the incident laser beam from a smooth surface, any lateral movement of the reflected beam caused by the ultrasonic waves is easily detected by a pair of photodiodes. The major disadvantage of the knife edge detector is that it does not cope well with optically rough surfaces, those that give a speckled reflection. The optical speckles from a rough surface adversely affect the efficiency of the knife edge detector, because ‘dark’ speckles move synchronously with ‘bright’ speckles, and their contributions to the ultrasonic signal cancel each other out. We have developed a new self-adapting sensor which can cope with the optical speckles reflected from a rough surface. It is inelegantly called the SKED—speckle knife edge detector—and like its smooth surface namesake it is simple, cheap, compact, and robust. We describe the theory of its operation, and present preliminary experimental results validating the overall concept and the operation of the prototype device.

Optical detection of ultrasound is achieved by measurement of the change in surface displacement, velocity, or angle [1, 2]. The two principal ways to detect these changes are using knife edge detectors (KEDs)—a technique also known as optical beam deflection—and interferometers. The KED is a particularly attractive device on account of its low cost and simplicity. As the sound wave propagates under the incident optical beam the reflected beam tilts backwards and forwards at the frequency of the ultrasonic waves. The optical beam is detected in a split detector, as in figure 1, so that in part of the cycle the signal in part A is greater than part B and in the other part of the cycle the signal B is greater than signal A. The outputs of the two detectors—either in terms of current or voltage—are subtracted one from the other using a differential amplifier, and the result is a signal proportional to the local tilt of the surface under the incident optical beam.

This works very nicely on optically smooth surfaces, where there is a single, specular reflection. On optically ‘rough’ surfaces, variations in the height of the sample at the laser beam focus cause different parts of the reflected beam to have different phase components, leading to local areas of constructive and destructive interference. This is known as speckle. This causes problems for the knife edge detector as the whole speckle pattern moves synchronously with the ultrasonic wave, assuming the amplitude is considerably lower than the acoustic wavelengths—in practice, true for all ultrasonic inspection. This means that the contributions from the ‘bright’ speckles moving from one photodiode to the other are cancelled out by the contributions from the ‘dark’

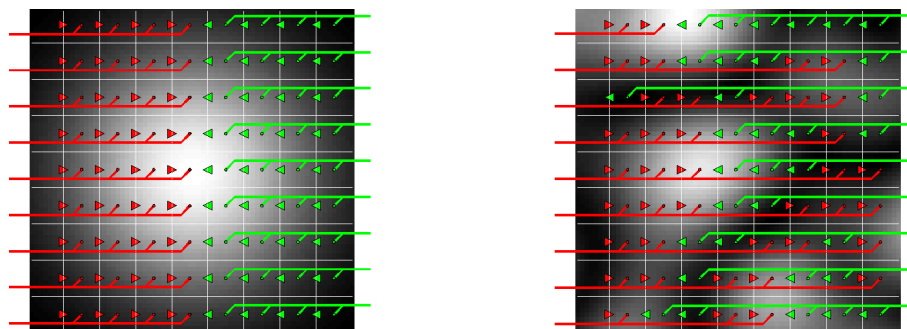




**Figure 1.** Principle of the conventional knife edge detector (KED). The difference between the electrical currents, proportional to the incident light in each half of the split detector, is determined by the difference amplifier.

speckles moving in the same direction. The result is a rapid decline in the signal to noise ratio of the signal with increasing surface roughness.

Some of the interferometric detection techniques are either inherently tolerant to speckle—such as the Fabry-Pérot interferometer [3]—or can be made to adapt to the speckle—such as those based on two wave mixing [4], or random quadrature demodulation [5]. In this paper, we describe how the optical beam deflection technique can be modified to be tolerant to optical speckle from rough surfaces. It is achieved by a novel design of an active adaptable photodiode pixel array sensor. It is inelegantly called the SKED—speckle knife edge detector—and like its smooth surface namesake it is simple, cheap, compact, and robust. We first describe the theory of its operation, and then present preliminary experimental results validating the overall concept and the operation of the prototype device.



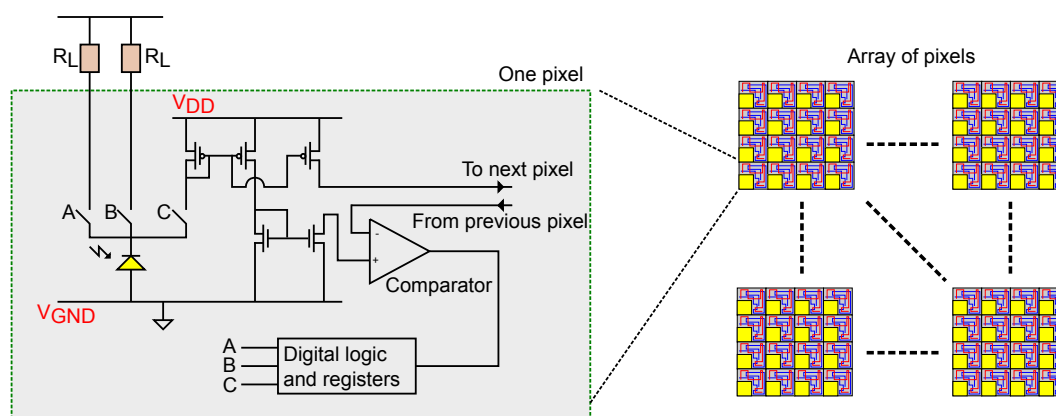
**Figure 2.** Schematic showing the operation of (left) the conventional knife edge detector, and (right) the speckle knife edge detector. The intensity gradient between adjacent pixels defines the output of one of those pixels.

The principle of operation of the SKED is illustrated in figure 2. The left hand image shows the reflected beam from a smooth surface so as this beam moves from left to right more signal is detected on the ‘green’ side compared to the ‘red’ side, exactly the same as in figure 1 above. When the light is reflected from a rough surface light breaks down into a speckle pattern with dark and light areas, moreover, its spatial extent becomes much greater. When the sound wave passes under the rough surface the speckle pattern will oscillate but the signal will not change on average since the light has been scrambled and there is no indication whether the left hand side signal will increase or decrease. If, however, we focus on a single bright speckle we will see it oscillate backwards and forwards giving periodic signal changes. The trick then is to redefine the regions where in the speckle pattern and feed them into the difference amplifier of figure 1. The SKED unravels the speckle by measuring the differences in light intensity across the detector array. Between pairs of adjacent pixels, the chip calculates whether there is more light falling on the left, or the right (represented by the left and right arrows of figure 2). If there is more light falling on the right, then the output from the right hand pixel is sent one way (coloured

red); if there is more light falling on the left, then the output from the right hand pixel is sent the other way (coloured green). If we subtract the sum of all the green pixels from the sum of all the red pixels, we get a signal proportional to the horizontal movement of the speckles, and hence of the local tilt of the sample surface caused by the ultrasonic wave.

The output is now the same as the conventional KED. Measurement of the intensity changes has simply allowed us to use the light reflected from the rough sample and reorganise it so that it behaves as if the reflection were from a smooth surface. The sensor configures its own architecture in response to the conditions of the reflected light. If the sound wave is propagating vertically rather than horizontally a conventional KED is insensitive to this motion, but the SKED allows us to address this by allowing the user to select whether to compare adjacent pixels horizontally or vertically.

The SKED device is a CMOS (complementary metal oxide semiconductor) integrated circuit, fabricated using a standard  $0.35\ \mu\text{m}$  4 metal layer process. The device consists of a  $32 \times 32$  array of pixels, plus some ancillary routing circuitry to send and receive digital and analogue signals off-chip. Each individual pixel consists of a photodiode which absorbs the incident laser light reflected from the sample under investigation, plus some digital logic and analogue components for mirroring and comparing the photocurrent. The fill factor is 54%. A simplified conceptual schematic is shown in figure 3.



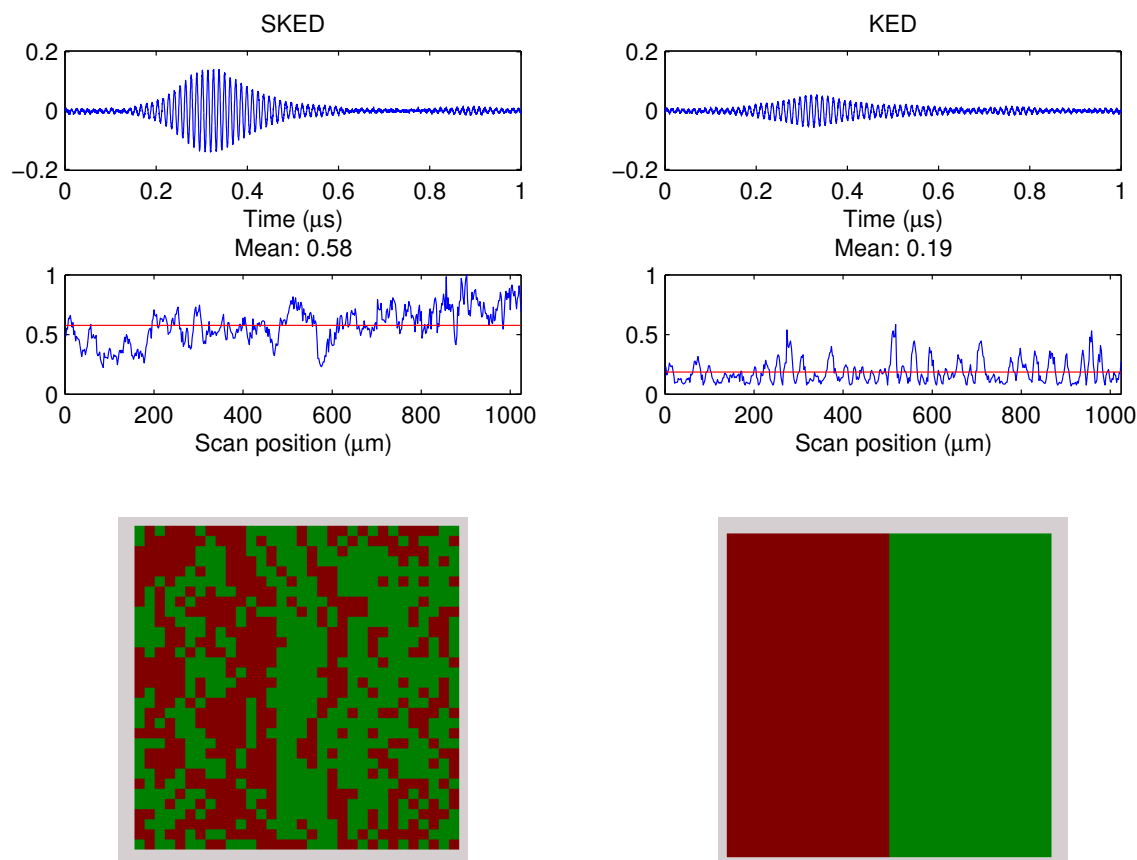
**Figure 3.** Conceptual schematic showing a single SKED pixel (left) and how this fits into the array of pixels in the SKED integrated circuit.

The SKED has two modes of operation: *configure* and *experiment*. In *configure* mode, all the pixels are isolated from each other—switches ‘A’ and ‘B’ in figure 3 are open, switch ‘C’ is closed—which allows the photocurrent of all adjacent pixels to be compared. The output of the comparator is used to determine whether one of each pair of pixels will be connected to channel A or B—this is actuated when the chip is put into *experiment* mode. At this point, all pixels are connected to one of the two analogue output channels.

In normal operation, the mode of operation would be synchronised to the ultrasound excitation source. Just prior to the point at which ultrasound needs to be detected, the SKED would be briefly put into *configure* mode, whereupon it would adapt to the optical speckle, before being returned to *experiment* mode which would allow the ultrasonic signal to be detected.

The device can also be programmed, in that the output channel of each pixel can be determined by the user. A programmable integrated circuit (PIC) provides an interface between the SKED IC and a USB connection to a host PC. This interface can also be used to read which output channel is active on each pixel.

Figure 4 illustrates the improvement that can be achieved in terms of signal consistency and



**Figure 4.** On the left, the SKED device automatically configures itself as a line scan is performed on machined aluminium; on the right, the SKED device is manually configured to behave as a conventional KED. The upper traces are the ultrasonic signals at the last point in the line scan. The centre traces show the mean signal level, normalised to the maximum of all recorded signals. The images at the bottom represent the configuration of the pixel outputs for the last point in the line scan.

amplitude (with respect to fixed noise levels) when the SKED device operates in self-adapting mode, compared to when it is manually configured to operate as a conventional KED with two fixed photodiodes. The ultrasonic signal is a laser-generated surface acoustic wave (SAW) packet with a centre frequency of 82MHz, on an aluminium sample with a machined surface. The theoretical bandwidth of the prototype device is 16MHz; this is limited by the capacitance of the photodiodes and the resistance of the transmission gates used to switch the output of each pixel to channel A or B. Despite this, the device is capable of detecting thermolastically excited SAWs at 82MHz, albeit with a first order filter roll-off of 20dB/decade.

We will fully characterise the device shortly and present the results in a future paper.

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