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Research Paper

A compact microwave device for monitoring insect activity in grain samples☆

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We designed and fabricated a novel microwave device capable of detecting a single insect in grain samples. A test set-up was constructed by combining a planar active microwave resonator, a Peltier cell, and an insect cage. With the integration of a regenerative element, the active resonator had a quality factor as high as 21,600 even when placed in grain, an electrically lossy medium. The high sensitivity of the device allowed the characterisation of the activity of single adult insects *Tribolium castaneum* or *Cryptolestes ferrugineus* at different temperatures, as well as the reliable detection of single adult insects in grain samples. Our approach demonstrated the non-contact sensing technique that could assist in decision making for integrated pest management programs to monitor insects in stored grain.

1. Introduction

Global climate change and increasing human populations demand a greater and more stable food supply. Stored-product insects infest stored grain around the world (Hagstrum, Phillips, & Cuperus, 2012). They reduce the quality and quantity of grain, and in several countries there is zero tolerance for insects in stored grain (Hagstrum & Subramanyam, 2006). These insect pests are small, difficult to detect and can quickly cause damage if undetected and not controlled. The current methods (Hagstrum & Subramanyam, 2006) of detecting stored-product insects include manually or mechanically retrieving samples and manually investigating for insects by sieving the sample (Jian, Doak, Jayas, Fields, & White, 2016), using a Berlese funnel to force internal insects

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out of wheat kernels (Hagstrum & Subramanyam, 2006), or placing traps inside stored grain bulks (Jian, Jayas, & White, 2014a). In laboratory settings, more sophisticated techniques such as acoustical methods (Gutiérrez, Ruiz, Moltó, Tapia, & Téllez, 2010), near infra-red (NIR) spectroscopy (Singh, Jayas, Paliwal, & White, 2009), electrical conductance (Brabec, Pearson, Flinn, & Katzke, 2010; Pearson & Brabec, 2007), and soft x-ray imaging (Karunakaran, Jayas, & White, 2003) have been used to detect insects in grain samples and inside individual kernels.

Researchers have also turned to microwaves as a tool for insect detection in grain products. Microwaves are especially useful because of their ability to penetrate common, non-conducting materials. Early uses involve radar techniques to detect insects. Microwave radar has shown to be an invaluable tool for studying airborne insect migration (Drake & Reynolds, 2012), and a radar device that can detect termites in walls is commercially available (Termatrac, 2017) and its application to stored product pest detection has been studied (Mankin, 2004). Furthermore, Jian, Jayas, White, Fields, and Howe (2014b) developed a technique using microwave heating combined with sieving to extract insects from grain more rapidly than the Berlese funnel method.

In addition to radar technology, microwaves have been used in passive planar cavities for the measurement of materials (Abduljabar, Porch, & Barrow, 2014; Boybay & Ramahi, 2012) and in biotechnology in applications such as the detection of single cell movement (Ferrier, Romanuik, Thomson, Bridges, & Freeman, 2009) and the assessment of yeast cell viability (Yang et al., 2010). These devices benefit from low power demand, compact size, on-chip integration, and the ability to perform non-contact sensing. Here, microwave cavities do not rely on the emission of microwave radiation but instead detect the changes in the resonant properties of the cavity when objects (such as moving insects) are present in the vicinity of the cavity. However, planar cavities suffer from significant radiative, conductive, and dielectric losses. As a result, the quality factor (Q factor) –which determines the sensitivity and resolution – of planar cavity sensors is limited to the order of 10^2 at room temperature.

Loss in the resonator can be compensated for with the integration of an active component whose amplifying features can restore lost energy (Nick, 2011). This produces a transmission spectrum with a much narrower transmission peak. Such active cavities or resonators exhibit drastically improved sensitivity and resolution as well as a resistance to lossy environments (where energy is dissipated by surrounding materials). Quality factors on the order of 10^4 are regularly achieved. The addition of an active component to improve the quality factor has been implemented in communication systems (Nick, Member, & Mortazawi, 2010), to study semiconductors (Jones, Kelly, Severtsen, & McCloy, 2013), and to sense liquids without contact (Zarifi & Daneshmand, 2015).

In this report, we propose a novel microwave based sensor for the monitoring of stored product pest insects. The sensing element of the device is a planar active microwave cavity constructed from microstrip with a Q factor as high as 21,600 even in lossy environments, which is a factor 900 greater than the conventional passive resonator ($Q = 24$) in the same environment. Our experimental objectives are to test: the sensitivity of the device to the movement of single insects; the dependence of the device response on insect activity; and the response of the device to the movement of insects in grain. In this study, we aimed to demonstrate the potential of the developed device as a means of rapidly detecting insects inside grain samples.

2. Materials and methods

2.1. *Experimental objectives and overview*

The goal of our experiments is to demonstrate the potential of active resonator technology as an insect detector in stored grain. Our goal was divided into three objectives. First, we sought to demonstrate that insect movement indeed produced a response in the active resonator when it came into contact with it. Second, we aimed to show that the resonator response was related to insect activity. Third, we sought, as a proof-of-concept, to demonstrate non-contact detection of insects in a grain sample.

To achieve our first objective, we placed individual adult insects in a closed area in contact with the device. We then recorded the resonator response for 10 min for indications of insect activity. The measurement was conducted at room temperature. This experiment, and all following experiments, were performed with adult *Tribolium castaneum* and *Cryptolestes ferrugineus* as test subjects.

We achieved our second objective by adjusting the temperature of the enclosed area and repeating the first experiment. We repeated the measurements at 10 temperatures between 10° and 50°. To obtain a statistical result, the measurement was replicated with 5 individuals from each insect species tested. We then combined the results to produce a plot of measured activity vs. temperature for each species.

A proof-of-concept for insect detection in grain was realised by filling the enclosed area with wheat grain, placing a single adult insect on the surface of the grain, and recording the resonator response for 10 min. We compared the response when an insect was present to when there were none. We repeated the measurement for grain depths ranging from 0.3 cm to 2.1 cm. The measurements were conducted at room temperature. We also compared the effect of the added dielectric loss of grain on passive resonators to that on active resonators.

2.2. *Experimental apparatus*

In order to test the resonator as a sensor, we constructed a device which integrates the resonator with the ability to confine insects, hold grain samples, and control temperature. Figure 1 illustrates the set-up for the experiments reported in this work. To prevent insects from escaping, a containment area was constructed on top of the resonator by fastening a 26 mm diameter, 80 mm high glass cylinder to the surface. The cylinder was closed at one end, and its open end was fixed to the resonator. To control the temperature, a Peltier cell was placed on the side of the board opposite to the resonator. The cell was supplied with a bench top power supply, and transferred heat to and from a metal optics table, which acted as a