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A novel ultra-high frequency humidity sensor based on a magnetostatic spin wave oscillator

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ABSTRACT

This paper presents a robust, simple and highly sensitive method to detect vapour compounds using a magnetostatic spin wave (MSW) tunable oscillator based on a yttrium iron garnet (YIG) epitaxial thin film coupled to a coplanar waveguide resonator. In this work, the device has been tested as relative humidity sensor. For this purpose, the coplanar waveguide resonator was coated with polyvinylpyrrolidone (PVP) polymer and used as a humidity probe. A dielectric change in the PVP due to a change in the ambient humidity introduces a fast phase shift in the probe, which causes a frequency shift in the MSW oscillator. The humidity sensing behavior of this device was investigated at room temperature over a range of 12.5–95% relative humidity (RH). Furthermore, the device was used to monitor human breath as a non-invasive sensor, showing great adaptability and ease of use in a real application. In conclusion, the sensor exhibited reproducibility, accuracy, high sensitivity, and fast response and recovery times. It also has the advantage of being simple and cost-effective.

1. Introduction

In recent decades, research has given rise to new, low-cost sensors to detect vapors in the environment, based on capacitive effects [1,2], resistive effects [3,4], optical fibers [5,6], field effect transistors (FETs) [7,8], surface acoustic waves (SAWs) [9,10] and quartz crystal microbalances (QCM) [11,12]. Many of the aforementioned devices have also been applied as air humidity sensors [13–20], and have been combined with different sensitive materials, such as porous ceramics [21,22], semiconductor materials [23,24] and polymers [25,26] in order to obtain a large response to changes in humidity. In general, the sensitive materials used to detect humidity are hygroscopic, which means that they attract and hold water molecules from the surrounding environment.

Research in improved humidity sensors is motivated by a need for humidity control in many industrial applications. In microelectronics, dry conditions are required in the processing of silicon wafers in a clean room. In agriculture, humidity affects seed quality, leaf growth, photosynthesis, pollination, occurrence of diseases, and, subsequently, economic yield. Additionally, humidity is crucial in many other fields, such as food storage, high-tech instruments, pharmaceutical and biomedical applications, etc. Thus, interest in humidity detection is growing rapidly.

On the other hand, tunable magnetostatic spin wave (MSW) oscillators based on yttrium iron garnet (YIG) have been used for more than fifty years in microwave instruments. In particular, magnetostatic surface wave (MSSW) oscillators have been researched for more than twenty years [27,28]. The main advantages of these oscillators over other magnetic oscillators such as the YIG sphere oscillator, is their planar configuration which makes them easier to integrate into circuits, and the fact that they work as delay lines. Among their many properties, it is interesting to point out their low propagation losses at microwave frequencies, their high loaded Q value, their small dimensions and their tuneability (from 0.2 GHz to 8 GHz). The oscillation frequency can be tuned by changing the magnitude of an applied magnetic field, while the wavelength remains constant. Consequently, numerous novel devices and applications based on MSW oscillators have been recently investigated [29–31].

In this paper we demonstrate the use of a tunable MSSW oscillator as a humidity sensor. A single stub in the form of a coplanar waveguide is connected to the oscillator circuit and is coated with a sensitive material to act as a vapour sensor. We use polyvinylpyrrolidone (PVP) as a sensitive material, which is highly hygroscopic and whose relative swelling in a humid atmosphere is documented in the literature [32]. In this way we show that changes

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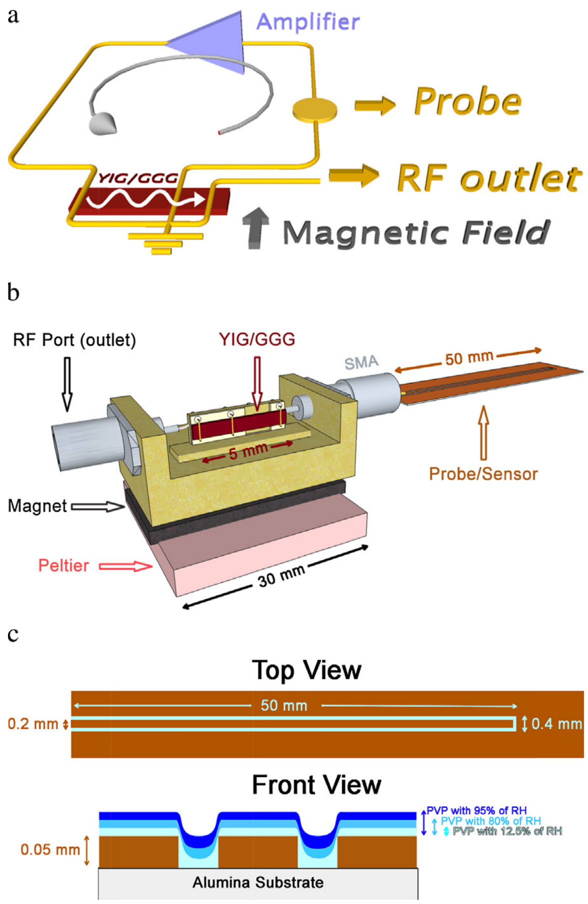

Fig. 1. (a) Scheme representing MSSW oscillator based on a two-port YIG delay line. (b) 3D scheme representing the MSSW oscillator coupled with the coplanar waveguide. (c) Front view of the probe and example of the PVP swelling for different RH.

in atmospheric humidity result in a significant frequency shift in the oscillator, giving rise to a highly sensitive humidity sensor.

2. Materials and methods

2.1. Magnetostatic surface wave oscillator

The MSW oscillator was based on a 5 mm × 2 mm rectangular ferromagnetic sample, composed of a 7.3 μm thick YIG film on a 0.5 mm thick gallium gadolimuim garnet (GGG) substrate. A two-port delay line whose insertion loss was approximately 10 dB between 0.2 GHz and 8 GHz, was formed by placing two antennas over the YIG film. This YIG delay line was introduced into the feedback loop of a solid-state amplifier, satisfying the criteria for oscillation: the total phase shift in the loop is $2\pi n$ (n = integer) and the gain over the closed loop is 1 (Fig. 1a). In this case a bias magnetic field applied perpendicular to the wave propagation direction and parallel to the YIG film plane, gives rise to magnetostatic surface wave (MSSW) propagation. This bias field was of 200 Oe and resulted in an oscillation frequency of about 1.2 GHz. In order to measure this frequency, a third antenna was placed in the feedback loop, providing an output signal of approximately 10 mW of power. Using a spectrum analyzer the linewidth of this signal was measured to be less than 1 kHz. The oscillator was tunable within a range of 0.2–3 GHz limited by the solid-state amplifier. However, with careful control over the bias magnetic field and with a suitable amplifier, the oscillation frequency can be extended to 8 GHz.

2.2. Coplanar waveguide probe

The coplanar waveguide consisted of a 0.5 mm thick substrate of alumina, coated with a 0.05 mm thick copper layer, in which a stripline with a width of 0.2 mm and a length of 50 mm was readily fabricated using low-cost lithography; the gap between the line and the ground was 0.1 mm. PVP is a water-soluble non-conducting polymer which has excellent wetting properties and readily forms films. This makes it suitable for use as a coating or an additive to coatings in a wide variety of fields such as medicine, pharmaceutical, cosmetic and industrial production. It is also used as a sensing material to detect VOCs in gas sensors. Here, pure PVP (Mw ∼360,000 g/mol) powder (Sigma–Aldrich) was dissolved in isopropanol to make a PVP solution with a concentration of 4% w/v. The probe was then spin coated with the PVP solution at 2000 rpm. The MSSW oscillator was coupled with the coplanar waveguide that worked as a humidity probe (Fig. 1b). Since PVP absorbs water molecules in the environment, the thickness of the polymer films changes significantly, modifying the permittivity in the gap of the coplanar waveguide, producing a perturbation in the confined electrical field. This causes a phase shift in the probe, and the phase variation in the probe induces a frequency change in the oscillator circuit, which we use to detect humidity. Fig. 1c presents different views of the probe: a top view shows the shape and dimensions of the probe, and a front view illustrates the relative swelling of PVP caused by absorption of water molecules when it is exposed to different relative humidities, resulting in different thicknesses of the PVP layer which affect the permittivity in the gap of the coplanar waveguide.

2.3. Experimental setup

The detection system consisted of a test chamber containing the humidity probe, coupled to the MSSW oscillator circuit whose output frequency was measured by means of a frequency counter. Since the magnetic field produced by the magnet is very sensitive to temperature, the magnet was kept at 25 °C, using a proportional integral derivative (PID) system that includes a platinum resistance (Pt100) and a Peltier device.

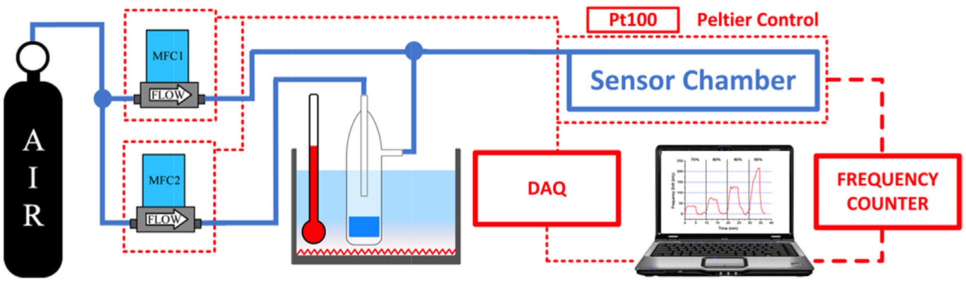

Fig. 2. Scheme of the instrumentation and experimental setup used for the data acquisition in real time.