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Interferometric near-field microwave microscopy platform for electromagnetic micro-analysis

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Abstract

We report an original near-field microwave microscope based on an interferometric technique for dielectric characterization in liquid media. The instrumentation combines a vector network analyzer, an interferometry-based matching network and dedicated evanescent microstrip probes fabricated in silicon technology. The measurement sensitivity of the measured microwave signals can be enhanced at the desired frequency in the range 1-26 GHz. Other advantages such as simplicity of operation and high spatial resolution are also achieved. As a demonstration, we have observed a high electromagnetic coupling between the probe tip and the liquid under investigation featuring emergent applications in biological and chemical researches.

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Keywords: Near-field microwave microscopy ; silicon probe ; evanescent waves ; interferometry ; liquid sensing.

1. Introduction

Microwave sensing methods are attractive for biological, food and chemical applications thanks to their high sensitivity to water. Although some of microwave methods are now well established, there is an urgent need to provide new measurement capabilities to address emerging applications. In particular, biological systems imaging in their saline solutions, accurate concentration determination of liquid solutions in food, medicine and pharmaceutical industries, glucose concentration measurement in blood, dielectric spectroscopy for water quality analysis are well-known scientific challenges to name a few of them [1].

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The volumes investigated in this kind of characterization are relatively small whereas the diffraction limit sets the spatial resolution achievable of conventional microwave methods to half the wavelength of operation. Thus, in the microwave spectrum spanning from 1 to 30 GHz, the spatial resolution is at the best in the order of the centimeter. Moreover, high measurement sensitivity is required to distinguish small dielectric contrasts. Narrow-band resonator methods with high measurement sensitivity have been demonstrated but are not well suited for high-loss media [2]. The major challenge of this work is to develop a new type of microwave instrumentation to meet the specific needs of spatially resolved characterization tools with enhanced measurement sensitivity. The technique proposal combines network analysis, microscopy and interferometry tools. In contrast with our previous works where coaxial probes are considered [3,4,5], in this study micrometric probe structures based on silicon technology are developed to confine the electromagnetic energy at the probe apex.

2. Microwave microscopy platform

The main measurement limitation in microwave microscopy applications is the impedance mismatch between the intrinsic impedance of the vector network analyzer (VNA) close to 50Ω and the impedance of evanescent microwave probes (EMP) that is in the range of tens or hundreds of kΩ [6,7]. So, there is an urgent need to develop new measurement techniques and dedicated instruments for impedances greater than the kΩ. The solution proposed consists to match the impedance of the EMP to 50Ω under any configuration. To that end, a reflectometry architecture build up with a hybrid coupler and an impedance tuner is proposed in Fig. 1. The hybrid coupler is connected to the port 1 of the VNA. The direct and coupled ports are connected to the EMP (with reflection coefficient Γ_{EMP}) and to the impedance tuner (with reflection coefficient Γ_{TUN}) respectively. In this configuration, the coupler has two functions. First, it acts as a reflectometer that separates the incident signal from the one reflected by the EMP. Secondly, by combining the reflected signal with the wave coming from the impedance tuner, it gives the possibility to tune the resulting signal to a very low level. This signal is measured in a transmission mode to overcome the main limitation encountered when using VNAs in terms of directivity errors, especially on the measurement of small signals. Thus, the technique gives the possibility to operate in the ultimate sensitivity range of the VNA.

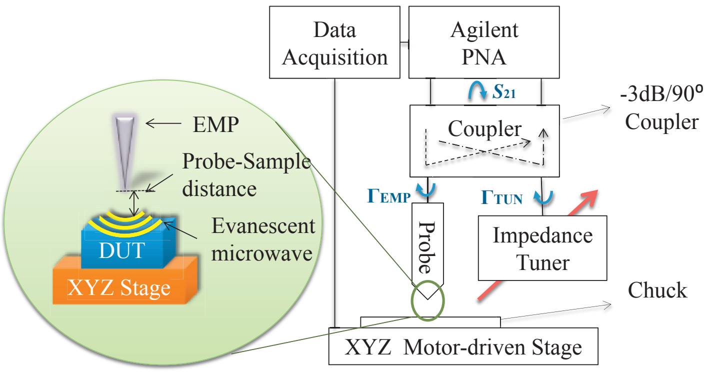


Fig. 1. Near-field microwave microscopy configuration based on interferometry.

The measurement system is a broadband network analyzer PNA-X N5242A (Fig. 2). The input arm of the coupler is connected to the test port of the VNA. The impedance tuner is built up with a high-resolution programmable delay line (Colby Instruments PDL-200A Series) connected to a motor-driven variable attenuator (ATM AF 074H-10-28). The output port of the attenuator is shortcut with a SMA short termination to operate in reflection mode. The sample to be scanned is mounted on a motor-driven xyz stage. The probe is positioned vertically over the stage. The xyz stage consists of three independent motorized linear translation sub-stages with respectively travel distances of 25 cm in x/y axis and 1 cm in z axis. The minimum increment step in the three directions is 1 µm. Consequently, the sample is positioned on the chuck fixed on the stage whereas the microwave part of the microscope remains fixed. In contrast with previous works related to the development of near-field microwave microscopes, a better stability is obtained by moving the sample under the probe tip instead of moving the probe. A camera is used for large-area visualization of the tip and the sample under test. Concerning the software part of the platform, a National Instruments Labview interface is developed to control the position of the sample, to set the network analyzer parameters, to measure the resulting transmission coefficient S_{21} and to display the results.

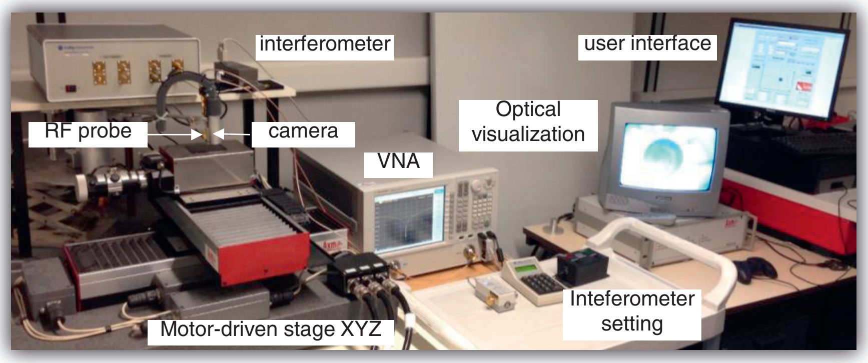
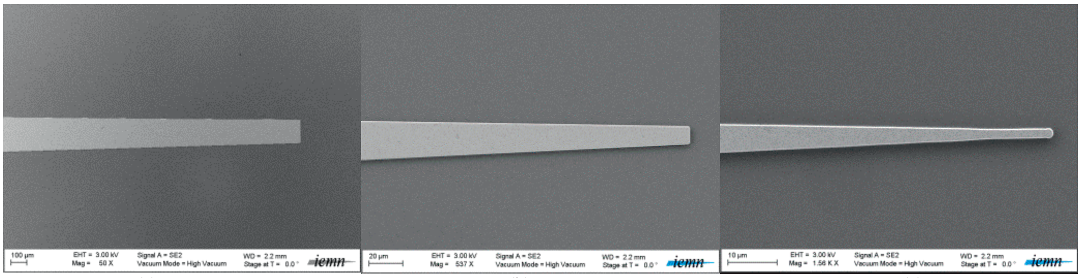


Fig. 2. Experimental set-up based on the proposed interferometric method for microwave microscopy applications.

Taking advantage of silicon micro-fabrication technology, we have developed a set of near-field microwave probes. The probes made of tapered microstrip gold (conductivity $\sigma = 5.8 \times 10^7$ S/m) lines deposited on a 480 µm-thick high resistivity ($5k\Omega.cm^{-1}$) silicon substrate have been fabricated to sense the evanescent interaction between the tip and the material under investigation. As the spatial resolution of microwave microscopy techniques is mainly governed by the apex size of the probe structure, different apex sizes have been considered depending on the lateral and depth resolutions required (Fig. 3).

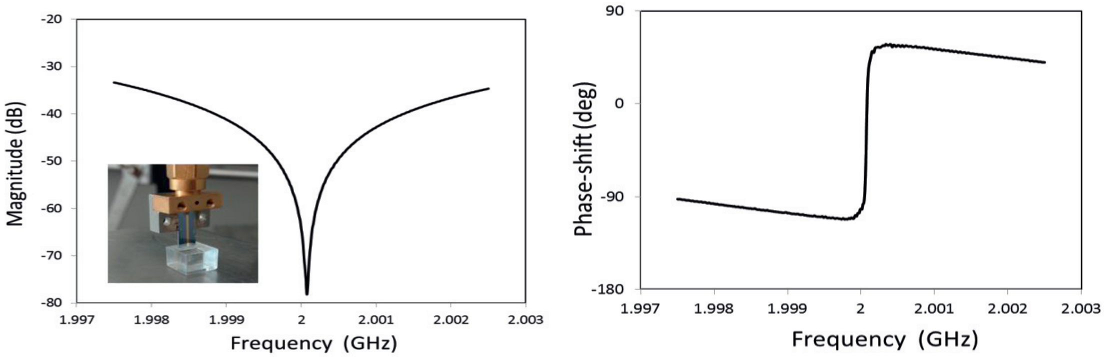


(a) (b) (c)

Fig. 3 Scanning electron microscopy photographs of the microstrip evanescent microwave tips with different apex sizes. (a) 100 µm. (b) 10 µm. (c) 1 µm.

3. Liquid sensing application

To demonstrate the sensitivity and accuracy of the tuning process, we considered the EMP with an apex size of 100 µm positionned above an open container filled with deionized water. The stand-off distance is set to 100 µm. The source power is set to 0 dBm and the intermediate frequency bandwidth (IFBW) to 100 Hz. In this configuration, the noise floor of the VNA obtained for the IFBW of 100 Hz is around -90 dB. A major advantage of the solution proposed is the possibility to tune the measured reflection coefficient to a very low value at the desired distance to the liquid under test. The potentialities of the technique are verified through a basic experiment that consists to adjust the magnitude spectra of the transmission coefficient S_{21} for a wave cancellation performed at the arbitrary test frequency of 2 GHz at a level of -80 dB (10 dB above the noise floor). The measurement is done at room temperature around 20°C. The data are acquired in the frequency range 1.997-2.003 GHz (Fig. 4). Fine adjustments of both the magnitude and the phase-shift of the transmission coefficient are performed to set the magnitude level of S_{21} to -78.2dB.



(a) (b)

Fig. 4 Microwave response of the probe-water interaction at a stand-off of 100 µm for a probe whose apex is 100 µm. (a) Magnitude of the transmission coefficient S_{21}. (b) Phase-shift of the transmission coefficient S_{21}.

In contrast with conventional resonators that exhibit a high unloaded quality factor that fails in the presence of the material under test, the interferometric process is performed in the presence of the material to achieve a high electromagnetic coupling that corresponds to a 3dB quality factor better than 8000. In this configuration, the measurement system is highly sensitive to any physical change of the liquid under test.

4. Conclusion

A near-field microwave microscopy platform was described. The resulting instrumentation combines a vector network analyzer, a coaxial evanescent probe, a hybrid coupler and a high precision impedance tuner. The method provides advantages such as broadband capabilities, high measurement accuracy and simplicity of operation. Based on this technique, a near-field microwave microscope for liquid sensing applications has been experimentally validated. The combination of a vector network analyzer and the proposed interferometer presents a viable and promising alternative to address the needs of characterization tools at the microscale for a wide range of applications.

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