Micromachined Near-Field Millimeter-Wave Medical Sensor for Skin Cancer Diagnosis

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***Abstract*— This paper presents the recent achievements in a project on micromachined millimeter-wave near-field medical sensors, in particular for skin cancer diagnosis. Micromachining enables sensor probes which achieve both high sensitivity and high lateral resolution through a drastically miniaturized probe tip. Two different design strategies are investigated: a broad-band, non-resonating, tapered dielectric-rod probe, and a resonance slot sensor. For probe characterization micromachined silicon test and calibration samples with tailor-made permittivity were fabricated. Characterization of fabricated prototypes show that the tapered probe can clearly and reproducibly distinguish silicon test samples of permittivity corresponding to healthy and cancerous skin tissue at 100 GHz. For the resonance slot probe the simulated response to materials of different permittivity is shown. Furthermore, the paper presents the design of phantom materials for probe evaluation on soft-matter dielectrics.**

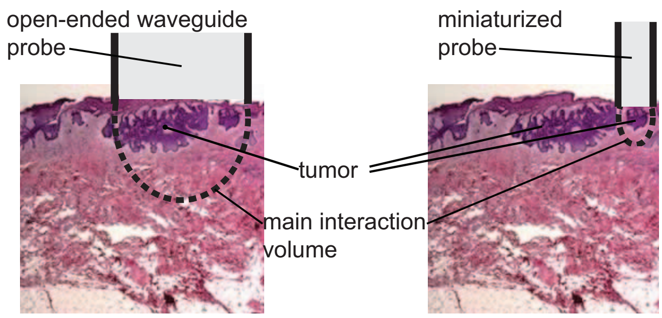

Figure 1. Microwave interaction volume for different probe sizes: (left) conventional probe, not resolving shallow cancer layers; (right) proposed miniaturized probe: high lateral resolution and penetration depth adapted to early-state skin-cancer layer.

I. Introduction

Skin cancer commonly affects also people in young age groups and incidents are increasing each year by almost 3% in Europe and North America. The estimated numbers for malignant melanoma, the tumor type which causes the majority of skin cancer related death, are 76000 diagnoses and 9000 caused deaths in the USA alone in 2012 [1]. To find one melanoma screening of 50 to 250 people is necessary and there still does not exist any reliable skin-cancer sensor technology that is used in the hospitals. Diagnosis is nowadays done by visual inspection by highly trained dermatologists, which is expensive and time consuming. An early diagnosis, when the tumor is still small, is crucial, since the risk for metastasis and therefore mortality increases with increasing tumor thickness.

Cancer tissue has a higher water content than healthy tissue [2] which leads to higher absorption of microwaves in cancer tissue. Therefore, microwave reflection (S_{11}) measurements can be used to diagnose cancer [3], including skin cancer [4]. However, conventional open-end waveguide probes, which so far have been used to prove the measurement concept on skin [5], do not have sufficient lateral and vertical resolution for detecting small early-state skin tumors and small tumor speckles (Fig. 1). Thus, there is a need for miniaturized sensor which has both high resolution and high sensitivity.

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II. Designs and Fabrication of Micromachined Near-Field Probes

Two different approaches are followed in the project: a broad-band, non-resonant tapered dielectric-rod probe, and a resonant-slot probe.

A. *Tapered Dielectric-Rod Probe Design*

The design of the tapered dielectric-rod probe is shown in Fig. 2. The metallized dielectric-rod waveguide, made of high-resistivity silicon, is tapered towards the tip and matched to the expected permittivity parameters of skin at 100 GHz (ε_r'=5.5 and ε_r''=5.4 for healthy, and ε_r'=6.5 and ε_r''=6.4 for cancerous skin tissue, for $\varepsilon_r = \varepsilon_r' - i\,\varepsilon_r''$, parameters from a 2nd order Debye skin-tissue model [7]). The design results in a drastically reduced tip size (down to 6% of the open-end waveguide area) and in high resolution without substantially compromising in sensitivity, i.e. energy-coupling into the dielectric test material. The dielectric-rod waveguide is accurately held in place by a micromachined holder and is fed via a dielectric wedge transition from a standard WR-10 waveguide connected to a vector network analyzer (VNA). The probe design and first data on probe characterization has recently been published in [6].

Both the probe and the holder are fabricated from a 600 μm thick high-resistivity silicon wafer with a silicon dioxide mask by deep reactive ion etching in an inductively-coupled plasma etcher. The probe is uniformly metallized in an electron-beam evaporator in four steps utilizing micromachined masks to shadow the non-metallized parts (Fig. 3).

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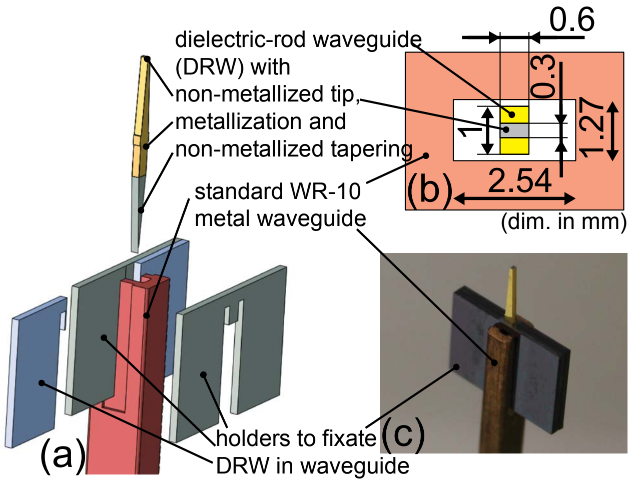

Figure 2. Design of the dielectric-rod probe and its fixture in a standard metal waveguide: (a) exploded CAD drawing; (b) schematic top view; (c) photograph of fabricated device.

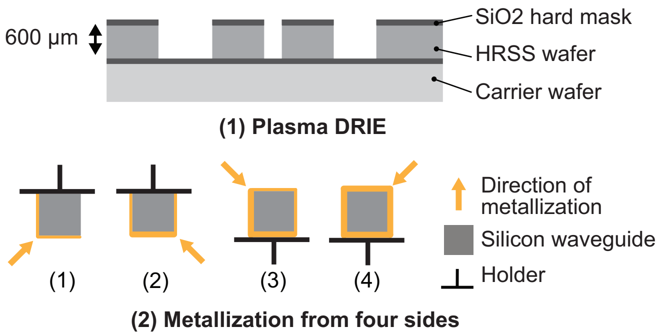

Figure 3. Fabrication is done in two major steps: (a) through-wafer deep reactive ion etching (DRIE) of high resistivity silicon substrate (HRSS) wafer with SiO_2 hard mask; (b) 4-side shadow-mask gold metallization by evaporation.

B. Resonant Slot Probe Design

The second probe investigated in this project is shown in Fig. 4. The permittivity detection is based on the resonance of a slot with dimensions 50 µm x 1000 µm in the metallization of the probe. The height of the waveguide probe is chosen to be 200 µm for matching to the iris realized in an aluminum flange, with dimensions 210 µm x 610 µm, holding in place the probe and closing the standard WR-10 waveguide connected to a 75-110 GHz vector network analyzer. The probe is also fabricated in high-resistivity silicon by micromachining using the same process flow as for the tapered dielectric-rod probe (Fig. 3); the resonance slot in the metal is patterned using focused ion beam (FIB).

III. Test Samples for Probe Characterisation

A. Micromachined Silicon Test Samples with Tailor-Made Permittivity

For probe characterization special micromachined test samples with tailor-made effective permittivity were fabricated from a

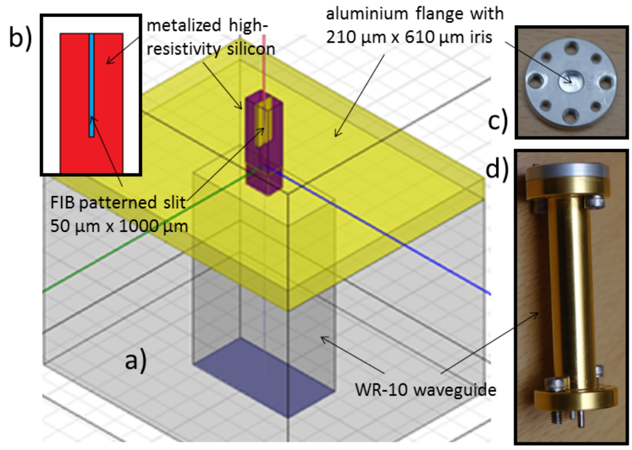

Figure 4. Design of the resonant slot probe: (a) CAD model of the probe, (b) inset shows the FIB patterned slit in the metalized high-resistivity silicon resonant probe, (c) custom-made flange with iris and (d) WR-10 waveguide.

350 µm thick Si-wafer by deep reactive ion etching (Fig. 5). The effective permittivity of the sample is determined by the size of the etch holes in a periodic pattern with a 100 µm pitch, which is substantially smaller than the wavelength. Test samples with different loss factors can be fabricated by using silicon wafers with different conductivity. These test samples allow for mimicking the microwave properties of tissue of varying water content, and guarantee for high reproducibility which is important especially for initial sensor development. Furthermore, micromachined test samples can be created with any given pattern of locally modulated permittivity, mimicking skin anomalies. The test samples can also be stacked on top of each other to mimic skin tissue consisting of different layers.

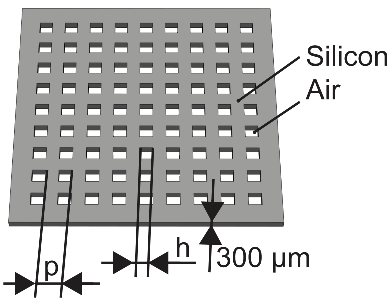

Figure 5. Silicon test sample schematically; the tailor made permittivity is determined by the ratio between the hole size *h* and the sub-wavelength pitch *p*.

B. TX 151 – Agar based Skin Phantom

At frequencies above 30 GHz the dielectric properties of skin depend highly on its free water content. The dielectric properties are extrapolated matched to double Debye. Agar based phantom are commonly used in research on interactions of microwaves with tissue. A phantom was fabricated with dielectric properties in the range expected for skin at frequencies around 100 GHz. Fig. 6 shows the dielectric behavior of the skin phantom.

The main constituents used to fabricate the phantom are deionized water, agar, polyethylene powder and TX-151. The concentrations are given in Table.1. Since the skin is a high water content tissue, water is chosen as the main constituent of the proposed phantom; it primarily determines its dispersive behavior in the considered frequency range [8]. Agar is employed for the retention of self-shaping, and its contribution to the phantom dielectric properties is negligible. Polyethylene powder is used to decrease the real and imaginary parts of the permittivity. The viscosity of the agar solution is increased using TX-151, since agar and polyethylene powder cannot be mixed directly.

TABLE I. CONSTITUENTS OF THE SKIN PHANTOM

Ingredients	Mass (g)
De-ionized water	100
Agar	1.5
Polyethylene Powder	20
TX 151	2.5

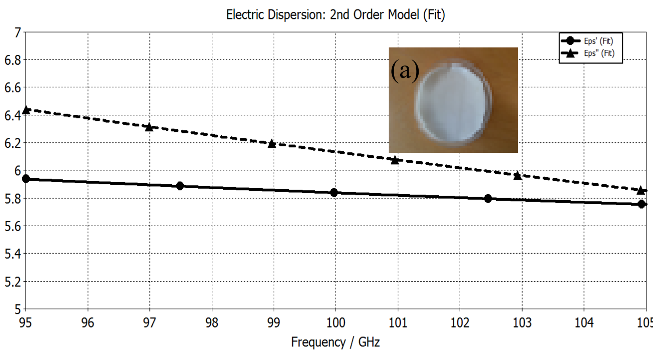

Figure 6. Complex permittivity of skin phantom and (a) photograph of skin phantom.

IV. RESULTS

A. Reflection Measurements with Dielectric-Rod Probe

For probe characterization reflection measurements were conducted on micromachined silicon test samples with different permittivity using an Agilent E8163A vector network analyzer with millimeter-wave measurement heads up to 110 GHz. For the measurement the tip of the dielectric probe is put in contact with the test sample and the return loss (S_{11}) is measured. On every test sample the return loss was measured in ten randomly chosen spots. After every five measurements a reference measurement against air was taken In Fig. 7 the results of the measurement on eight different test samples with permittivity values in the range of skin tissue are shown and the expected permittivity values for healthy and cancerous skin tissue are indicated. As expected, a clear dependency of the measured return loss on the sample permittivity can be seen and a sample with the expected permittivity of cancer tissue can clearly be distinguished from one with the permittivity of healthy tissue. This proves the potential of the probe for diagnosing skin cancer. Differences between measurements on the same test sample are mainly caused by the imperfect positioning of the tip on the sample resulting in varying, small gaps between both. However, the operator influence repeatability was found to be 1.36% (1σ) of the power level. The lateral resolution was recently characterized to better than 200 μm for a probe with a tip size of 0.3 x 0.6 mm^2 [9].

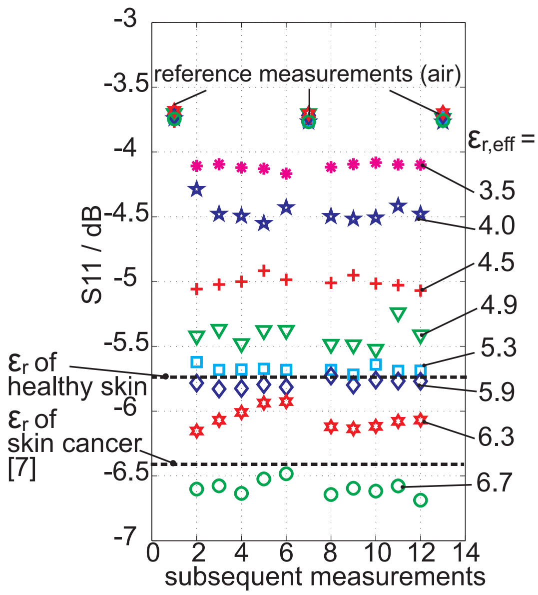

Figure 7. Measured return loss at 100 GHz on silicon test samples of different effective relative permittivity $\varepsilon_{r,eff}$ using a non-resonant dielectric-rod probe with a 0.3x0.6 mm^2 tip.

B. Simulation Results of Resonant Probe

The simulation of the resonant probe is assessed with different relative permittivity (ε_r) ranging from 1 to 11 in steps of 2 and from 20 to 50 in steps of 10, as presented in Fig. 8. As can be seen, the probe is well matched and the variation in permittivity spans over approximately a range of 200 MHz.

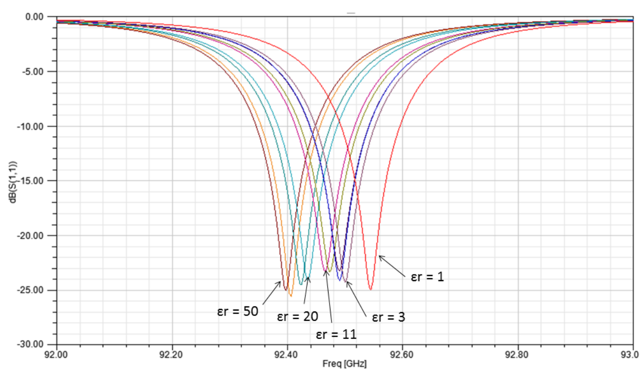

Figure 8. Simulation of the resonant probe, assessing different relative permittivities ranging from 1 to 50.

V. CONCLUSION

This paper presents two different approaches for a high-resolution millimeter-wave probe for skin cancer diagnosis. Measurements with a prototype of the proposed broad-band near-field probe show high sensitivity in a permittivity range which includes the expected values for healthy and cancerous tissue, as well as high measurement reproducibility and long term stability of the measurement setup. The simulation of the resonant-slot probe also shows good sensitivity to different permittivity values. For probe characterization micromachined silicon test samples with tailor-made permittivity are used, which mimic the dielectric properties of skin tissue and are well suited to evaluate the fabricated probes and compare different probe designs. Furthermore agar based skin phantoms were made which will be used for evaluating the probes on soft-matter dielectrics. The presented probe designs combine high resolution and high sensitivity, which is important for the diagnosis of small and inhomogeneous skin tumors.

ACKNOWLEDGMENT

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