Novel rf power sensor based on capacitive MEMS technology

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Abstract
We present the theory, design, fabrication of and first measurements on a novel power sensor for radio frequency (rf) signals, based on capacitive measurements. The novelty of this sensor is that it measures the force that is created between the rf signal and a grounded membrane suspended above the line were the signal is traveling. Deflection of the electrode is measured capacitively, and the power is then deduced. In this case, a “through” power sensor is realized, which means that the signal is available during the power detection.
Key Words: “through”, radio frequency, power sensor, capacitance readout, MEMS.

I. INTRODUCTION
Nowadays, the available technology for power detection of rf signals is based on thermistors, thermocouples and diodes. All these are terminating devices, i.e. the signal is dissipated, and therefore lost, during the power measurement. A novel philosophy for power detection has been recently proposed, in order to keep available the rf signal while its power is being measured [1-3]. The power measurement is based on the movement detection of a grounded membrane suspended above a planar transmission line where the signal is traveling. This displacement is measured capacitively. In the first part of this paper, the operation principle of the sensor will be explained. Then, the design and fabrication is shown. Finally the experiments on first prototypes are presented and compared to theory.

II. OPERATION PRINCIPLE
The power of an rf signal that is transported on a transmission line with characteristic impedance $Z_0$ is given by $V_{\text{rms}}^2/Z_0$, where $V_{\text{rms}}$ is the rms voltage of the rf signal. When a capacitor is connected in parallel with the transmission line, an electrical force will appear between the capacitor plates: $F=C(V_{\text{rms}}\cos\theta)^2/(2d)$ where C is the capacitance and $d$ is the distance between the capacitor plates. When one of the plates is movable supported with spring constant k, and the frequencies of the signal are much higher than the resonance frequency of the movable plate, the plate is only sensitive to the rms value of the force, that is proportional to the power level: $F=CV_{\text{rms}}^2/(2d)$. Therefore, the power level can be deduced by detecting the movement of the plate. In practice the movement is detected as a capacitance change between a measuring electrode and the movable plate.

The addition of the capacitor will change the impedance of the transmission line and hence reflection losses are introduced. The reflection parameter is given by $S_{11}=10\log(|\Gamma|^2)$ where $\Gamma=(Z-Z_0)/(Z+Z_0)$ and $Z=Z_0$ // 1/ωC. The transmission parameter, assuming no conduction and dielectric losses, is given by $S_{12}=10\log(1-|\Gamma|^2)$. The minimum power that can be detected is primarily limited by the measuring electronics and ultimately by the thermo-mechanical noise of the membrane.

III. DESIGN
Figs. 1 and 2 show schematic drawings of the first prototype of the power sensor.

![Fig. 1. Drawing of the sensor (top view).](image-url)
The rf signal is transported by a Coplanar Waveguide (CPW). The width, thickness and distance between lines of the CPW were designed in order to get 50 Ω characteristic impedance. At a certain position, an aluminum membrane is suspended above the central line of the CPW and connected to the ground planes, resulting in a grounded moving plate. In this way, a capacitor is created. Then, a force appears as mentioned in the previous section, and the membrane deflects. The deflection is measured by sensing the changes in capacitance between the membrane and the measuring electrodes placed next to the central line of the CPW. The width, w, was chosen to be 300 μm for all membranes. Three different lengths (L=200, 1800 and 3600 μm) were designed in order to test the response for different capacitance values.

III. FABRICATION
The fabrication was done by aluminum surface micromachining. The schematic of the fabrication process is shown in figure 3:

An AF45 glass substrate was used because of the low losses for rf signals (\(\varepsilon_r=6.2\), \(\tan\delta=9\times10^{-4}\) at 1 MHz). The CPW and measuring electrodes were fabricated by sputtering of a 3 μm thick aluminum layer (Fig. 3.1). Then, a 1.8 μm thick photoresist layer was deposited in order to determine the gap distance (Fig. 3.2). The membrane was made by sputtering of a 1 μm thick aluminum layer (h) (Fig. 3.3). In the last step, the membrane is released by etching the photoresist by oxygen plasma etching (Fig. 3.4).

SEM pictures of the devices are presented in Figs. 4 and 5.
IV. EXPERIMENTS

For the characterization of the rf response of the power sensor, measurements of S-parameters were done with an HP 8510C Network Analyzer and using a Cascade Microtech 9000 probe. Figure 6 shows $S_{11}$ measurements from a CPW with different membrane dimensions. A good agreement between theory and experiments is presented, therefore, any $S_{11}$ response can be achieved (always above of the CPW limitation) by using the correct capacitance value. For the theory, the change in characteristic impedance due to the added capacitance is considered without fitting parameters.

![Graph showing $S_{11}$ parameter measurements](image)

Fig. 6. $S_{11}$ parameter measurements (symbols) and comparison with theory (lines).

![Graph showing $S_{12}$ parameter measurements](image)

Fig. 7. $S_{12}$ parameter measurements (symbols) and comparison with theory (line).

Fig. 7 shows that the transmission losses are slightly higher than predicted. On the other hand, the difference between $S_{12}$ for the sensor and for a bare CPW is much smaller. This indicates that the transmission losses due to the CPW itself are more important that the reflection losses from the membrane. In fact, the transmission losses are in good agreement with the CPW losses presented in [4]. Since the length of the CPW is 6 mm (more than needed for the sensor), better results could be achieved by using shorter transmission lines.

The deflection of the membrane was detected by measuring the change in capacitance between the measuring electrodes and the ground using the electronics shown in the figure 8.

![Schematic of the electronics](image)

Fig. 8: Schematic of the electronics used for movement detection based of capacitance readout.

The dc voltage at the output is proportional to the capacitance between the membrane and the measuring electrode, and then the deflection of the membrane is detected.

The first movement measurements were done by applying a dc voltage, $V_{dc}$, between the central line and the ground of the CPW (and therefore, between the central line and the membrane). Fig. 9 shows a measured quadratic relationship between the increase of $C$ and $V_{dc}$. The electrical force is proportional to $V_{dc}^2$ and gives a linear displacement of the membrane. When we apply rf signals we are controlling the power, and a linear relation between capacitance change and rf power is then expected. This is confirmed by the measurements in Fig. 10, obtained for signals of 2.5 GHz. From this graph we can deduce the sensitivity factor of the hf power measurement: $dC/dW = 0.437 \, \text{pf/mW}$. 

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REFERENCES


V. CONCLUSIONS

We have presented a new capacitive rf power sensor based on MEMS technology. The sensor is based on a force detection that is proportional to the power and it does not dissipate the power of the signal, this being a main advantage compared to the existing technology for rf power sensors. Theory has been presented and compared to rf measurements. The first experiments are presented as a proof of the operation principle.