A Novel Additively-Manufactured Pressure Transducer for Zero-Power Wireless Sensing

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***Abstract* — This work presents a pressure transducer consisting of a 3D coupled-line directional coupler, where the distance between lines varies with the applied pressure. In particular, two quarter-wave microstrip lines facing each other are aligned one on top of the other so that part of the signal flowing in one line is coupled to the other line. When pressure is applied, the distance between lines reduces, while coupling increases. That way, different pressure levels are converted into different coupling values. Two parallel-plate waveguides connect the microstrip line on the top layer to the bottom layer, so that all four ports of the directional coupler are realized on the same layer. The circuit is manufactured with stereolithography 3D printing. Selective metallization is performed embossing the desired patterns on the 3D printed dielectric and then applying silver nanoparticle ink to the protruding areas with a brush. A proof-of-concept prototype, working at 3 GHz, was manufactured and tested. The proposed prototype features a change of the transmission coefficient between the input and the coupled ports from -15.6 dB to -12.4 dB for an applied pressure of 278 kPa compared to zero pressure state, thereby proving the working principle of the circuit. The proposed transducer can be used in a harmonic transponder, and the pressure information can be retrieved from the amplitude difference of the signals at the direct and coupled ports. The obtained results open the door to a new class of pressure transducers that are based on additively-manufactured radio-frequency components, and are suitable for passive wireless sensors.**

***Keywords* — 3D printing, additive manufacturing, directional couplers, Internet of Things, pressure sensors, pressure transducers, stereolithography, transmission-line transitions**

I. Introduction

The Internet of Things (IoT) has enabled a paradigm shift in resource management: the presence of sensors and transducers that can acquire and communicate real-time information about environmental parameters associated with the state of goods and infrastructures has the potential to reduce waste and resource usage, guarantee timely maintenance, and prevent risks for human health [1].

However, the effectiveness of the IoT approach depends on the possibility to deploy a large amount of sensors in the environment to get information with a suitable spatial sampling. Therefore, there is a need to develop ambient sensors which are low-cost, compact, robust, and possibly passive, since managing the battery replacement of this large amount of sensors will soon become infeasible [2]–[3]. The environmental impact of IoT circuits is also of major concern, due to the high volume of sensors to be manufactured [4]. To this purpose, 3D printing and, more generally, additive manufacturing technologies can help reduce material waste and cut manufacturing time and costs [5], enabling the adoption of innovative materials which combine tailored chemical, electromagnetic and mechanical properties. Additionally, 3D printing can be used to realize 3D sensors not feasible with standard subtractive technologies.

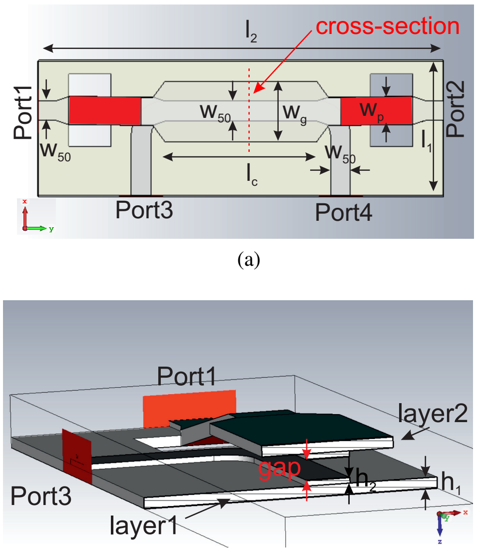
Among ambient sensors, pressure sensors are currently attracting attention, as they find application in several fields, ranging from healthcare and wearables [6], to wear monitoring in industrial equipment [7]. State-of-the-art pressure sensors are usually based on piezo-electric or piezo-resistive materials [8], [9]. However, the processes needed to manufacture piezo cantilevers are typically different from the ones used for the rest of the circuitry, which adds complexity to the manufacturing procedures [10]. Additionally, piezoelectric crystals are brittle, and some of the most popular piezoelectric materials include toxic components.

In this paper a 3D printed pressure transducer is described, which does not require any piezo-electric or piezo-resistive material, and can be integrated in a passive wireless transponder conveniently. The structure proposed here as a pressure transducer was firstly presented in [11], where, however, it was investigated as vibration transducer. The paper is organized as follows: Sec. II illustrates the detailed design procedure of the pressure transducer and its integration with a wireless passive transponder; then, the experimental results are presented in Sec. III and, finally, in Sec. IV the conclusions are drawn.

II. Theory of operation

The proposed pressure transducer is based on two coupled quarter-wave microstrip lines placed in front of each other, as shown in Fig. 1.

The line on the top layer (called layer2) is connected to the bottom layer (layer1) using two parallel-plate waveguides (in red in Fig. 1(a)). Each side of the paralel-plate waveguide is connected to a microstrip line with a transmission-line transition: each plate of the parallel-plate waveguide transforms into a strip at one end and into the ground plane at the other end using a linear taper. This way, the microstrip line on the top layer is “twisted” on the bottom layer, the four ports connected to the two microstrip lines lie on the same layer, and the transducer can be easily connected with



(a)

(b)

Fig. 1. Circuit layout: (a) top view and (b) cross-section. The main parameters are: $w_{50} = 3.3\,\text{mm}$, $w_p = 4.6\,\text{mm}$, $w_g = 10\,\text{mm}$, $l_1 = 21.8\,\text{mm}$, $l_2 = 67\,\text{mm}$, $l_c = 29\,\text{mm}$, $h_1 = 0.85\,\text{mm}$, $h_2 = 0.4\,\text{mm}$, and $gap = 1\,\text{mm}$. After [11].

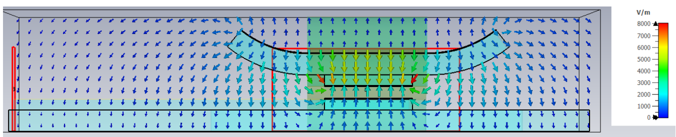


Fig. 2. Electric field distribution on the plane perpendicular to the coupled lines at 3 GHz.

the rest of the circuit components. The design is conducted using full wave simulations within CST Microwave Studio. The circuit is designed for a frequency $f_0 = 3$ GHz for demonstration purposes. All lines are matched to $50\,\Omega$.

The parallel-plate waveguide is also dimensioned for a characteristic impedance Z_0 of $50\,\Omega$, as follows:

$$Z_0 = \frac{\eta h_p}{w_p}, \tag{1}$$

where η is the intrinsic impedance of the substrate, h_p is the distance between the parallel plates, and w_p is the plate width. Two rectangular apertures are realized on the ground plane of layer1 to allow for the connection between the parallel plate waveguides and the microstrip line on layer1.

Due to the close proximity of the two microstrip lines (the distance between the coupled lines is called "gap" in Fig. 1), power can be effectively coupled between the lines. The two coupled lines form a 3-D directional coupler, where Port1 is the input port, Port2 is the direct port, Port3 is the isolated port, and Port4 is the coupled port, according to the numbering reported in Fig. 1(a).

Fig. 2 shows the amplitude of the total electric field (both tangential and normal components) on the plane perpendicular to the coupled lines at 3 GHz for $gap = 0.5$ mm, assuming that the power is fed at Port 1. The field is clearly coupled to the second line laying on layer1 as expected.

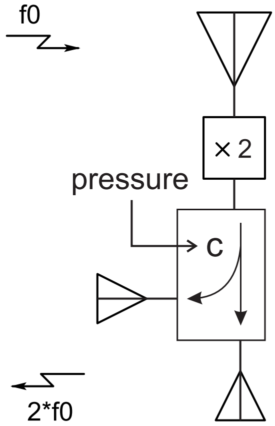


Fig. 3. Schematic representation of the proposed wireless pressure sensor node.

By applying a pressure on the top layer, the distance between the two lines varies, thereby modifying their coupling coefficient. Therefore, the transmission coefficient between Port1 and Port4 increases as the applied pressure increases. On the other hand, the transmission coefficient between Port1 and Port2 slightly decreases as the line distance decreases. Therefore, the coupling factor C of the directional coupler is a function of the applied pressure P:

$$C = C(P). \tag{2}$$

The information acquired with the proposed pressure transducer can be conveniently transmitted using a passive harmonic transponder. The schematic of the proposed transponder is shown in Fig. 3. The input antenna of the tag acquires the interrogating signal at f_0. The signal is converted to the second harmonic using a frequency doubler, such as the one presented in [13]. Then, the output port of the doubler is connected to the input port of the pressure transducer. The isolated port of the transducer is terminated on a $50\,\Omega$ matched load. The direct port is connected to an antenna which transmits in vertical polarization, while the coupled port is connected to an antenna which transmits in horizontal polarization. This way, the signal at the direct port acts as an amplitude reference for the signal at the coupled port of the directional coupler, and the pressure information can be retrieved from the amplitude ratio of the signals radiated in the two orthogonal polarizations. This information can be retrieved with an I/Q receiver.

III. Experimental Results

The transducer is realized for demonstration purposes with low-cost additive manufacturing technologies. The dielectric scaffolding is 3D-printed using stereolithography. The solid object is generated by laser-curing a liquid photoreactive resin. The "clear" resin from FormLab is used. In the operating frequency range of the transducer the resin features a permittivity $\epsilon_r = 2.8$ and a loss tangent $tan\delta = 0.03$ [12]. The metal patterns are realized by applying silver nanoparticle ink to the 3D printed surface with a brush. In

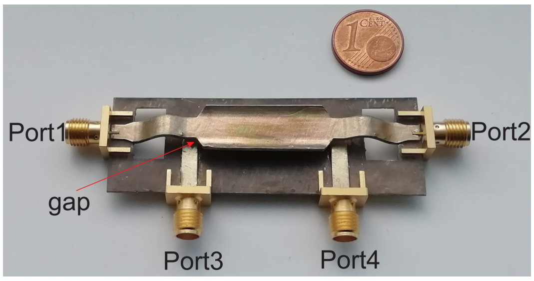


Fig. 4. Photo of the circuit prototype. After [11].

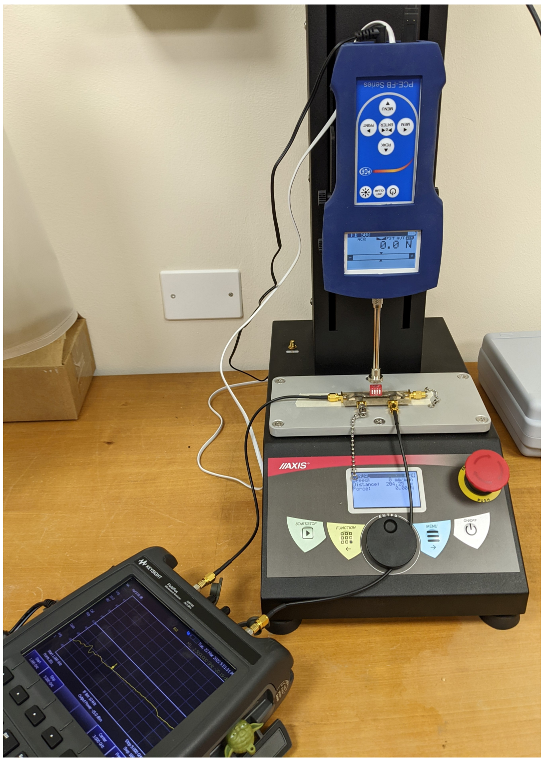


Fig. 5. Photo of the experimental setup used to test the proposed pressure transducer.

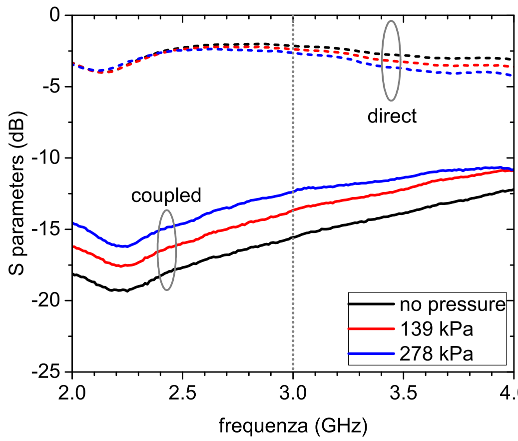


Fig. 6. S parameters of the transducer for different pressure values. The dashed curves represent the transmission coefficient between the input and the direct ports, while the solid curves represent the transmission coefficient between the input and the coupled ports.

the areas corresponding to the strips, the 3D printed dielectric is embossed (the depth of embossing is indicated with "h_2" in Fig. 1(b), and it is equal to 0.4 mm). This way, the rest of the surface is not touched during the metallization process. Four/five ink layers are deposited, and the sample is cured at $110\,^{\circ}$C for 10 minutes after each ink deposition, to obtain a satisfactory conductivity (about 1×10^6 S/m).

A photo of the manufactured prototype is shown in Fig. 4. The borders of the top layer are curved to ease the silver application to the microstrip lines. The waveguides form two arcs at the sides of the microstrip line on layer2. Four SMA connectors are attached to the two microstrip lines with a colloidal silver paste for measurement purposes.

A photo of the experimental setup is shown in Fig. 5. A compressive force is applied to the transducer, perpendicular to layer2 with a dynamometer (model PCE-FB 500), connected to an automatic vertical stand. The S-parameters of the transducer are measured with a vector network analyzer. The ports not involved in the measurement are closed on $50\,\Omega$ matched loads. The stand is programmed to move downward until it applies a given pressure (in the present work, 1 N and 2 N are applied to a surface of 0.72 cm^2, respectively, corresponding to 139 kPa and 278 kPa pressure). A constant force is applied for 10 sec, and then the dynamometer is programmed to return home. The S-parameters of the transducer are acquired during the hold phase after 8 seconds.

The measured transmission coefficient between the input and the direct ports (dashed lines), and between the input and the coupled ports (solid lines) are illustrated in Fig. 6. At 3 GHz, the transmission coefficient between the input and coupled ports increases by more than 3 dB, from -15.6 dB to -12.4 dB, in the considered pressure range. The transmission coefficient between the input and the direct port decreases from -2.1 dB to -2.7 dB. This corresponds to a sensitivity of about 0.013 dB/kPa, as shown in Fig. 7. It is worth mentioning that the circuit is broad band, since no resonant elements are present. Its operating band spans approximately from 2.5 to 3.3 GHz, maintaining similar sensitivity throughout this frequency band. At 2 N, the coupling factor C of the circuit starts to saturate with respect ot the applied pressure. This is due to the fact that the microstrip lines are in extremely close proximity.

It is worth mentioning that the sensitivity of the transducer can be easily tuned by varying the geometry of the structure, by modifying the initial "gap", and by choosing a dielectric material with a different Young modulus.

Due to the low coupling factor, which is typical of coupled-line directional couplers, the transmission coefficient between Port1 and Port4 is 13.5 dB below the transmission coefficient between Port1 and Port2 in absence of applied pressure. To ease the information recovery in case the transducer is used in the harmonic transponder shown in Fig. 3, more comparable values for the two transmission coefficients associated with the direct and coupled ports are desirable. For this purpose, a dissipative pad can be connected to port 2.

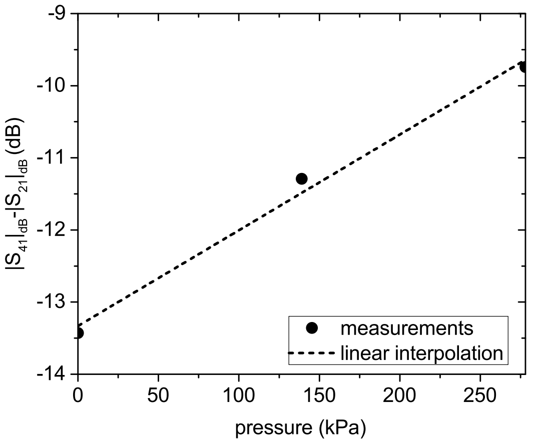


Fig. 7. Study of the transducer sensitivity at 3 GHz.

In the harmonic systems, the read range of the system mainly depends on the sensitivity of the receiver, and on the conversion loss of the frequency doubler responsible for the generation of the second harmonic [13]. In the present case, also the coupling factor plays an important role, since the tag backscatters power in the two orthogonal polarizations, and the read range is limited by the weakest signal.

By way of example, assuming to have a reader which transmits a sinusoidal signal at the frequency $f_0 = 2.4$ GHz (ISM band) with a power of 36 dBm EIRP, and to have a receiver with a sensitivity of -100 dBm, a wireless transponder characterized by conversion loss of 20 dB, antenna gains of 0 dBi, and a coupling factor of 16 dB, leads to a maximum read range of 2 m.

IV. Conclusion

A 3D printed pressure transducer has been presented, which consists of a 3D coupled-lines directional coupler. The sensor information (i.e., the applied pressure) has been encoded in the amplitude difference between the signals at the direct and coupled ports of the directional coupler. For demonstration purposes, the transducer has been manufactured using additive technologies (stereolithography 3D printing and ink deposition), and has been tested under different applied pressures, demonstrating that the difference between the signals at the direct and coupled ports varies from 13.5 to 9.7 dB at the operating frequency of 3 GHz. The schematic diagram of a possible harmonic transponders based on the proposed pressure transducer has been presented as well. The obtained results open the door to a new class of additively-manufactured pressure transducers, suitable for passive wireless sensors.

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