J. of Electromagn. Waves and Appl., Vol. 24, 1429–1437, 2010

A DISTANCE-COMPENSATED RADAR SENSOR WITH A SIX-PORT NETWORK FOR REMOTE DISTINCTION OF OBJECTS WITH DIFFERENT DIELECTRIC CONSTANTS

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Abstract—A distance-compensated radar sensor with a six-port network is proposed and successfully implemented to remotely discriminate target objects with different dielectric constants. The sensor simultaneously measures distance and reflection coefficients of the objects using DC output voltages of the six-port network, thereby obtaining a comparative profile of their dielectric constants with distance compensation scheme. The distinction of the target's dielectric constant profile is theoretically derived and experimentally demonstrated within a target distance of 1 m using a 24 GHz six-port radar sensor module. The die size of the six-port network MMIC is $2.0 \times 1.8\,\mathrm{mm}^2$, and the whole sensor module is realized in $3.6 \times 5.5\,\mathrm{cm}^2$, excluding a horn antenna and signal source.

1. INTRODUCTION

A dielectric constant provides many handy hints such as the electrical property of a target material, the composition ratio of a compound, and the amount of air or water in the material. For that reason, a sensor measuring the relative dielectric constant itself or a comparative profile of the dielectric constants is useful for many industrial

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applications such as non-destructive detection [1], breast cancer detection [2], and security systems [3]. Among previous methods for implementing the sensor, a free-space method at microwave frequencies has been of interest as it provides non-destructive and contactless characterization [4]. However, measurement errors of this approach are dependent on the distance between the antenna and target [5]. Therefore, a range finder and micro-positioning apparatus to fix the target at a specified distance should be simultaneously used.

A six-port network, consisting of several passive elements and diode power detectors, makes it possible to realize a high-accuracy radar sensor and can be utilized to discern dielectric constants because it was previously developed for a low-cost network analyzer or reflectometer [6, 7]. The six-port reflectometer could measure complex permittivity, but it was not compatible to a stand-alone remote sensor because the measurement was done only at the contact surface using an open-ended probe [8] or at a known distance, which also required additional positioning components [9].

This paper presents a stand-alone radar sensor with the six-port network to remotely discern relative dielectric constants of the targets using the proposed distance compensation scheme. Compared with the free space method, the developed sensor extracts reflection coefficients from DC voltages of four diode detectors and calculates the target distance, thereby obtaining distance-compensated dielectric constant profiles without any additional components.

2. PRINCIPLE OF THE DISTANCE-COMPENSATED RADAR SENSOR

When the round-trip time is 'T' in Fig. 1, the transmitted signal 's' and the received signal 'r' can be expressed as

$$s = A \cdot e^{j2\pi \cdot f \cdot t} \tag{1}$$

$$r = A \cdot e^{j2\pi \cdot f \cdot (t-T)} \cdot \sum_{n=1}^{\infty} \Gamma_m(n) \tag{2}$$

where f is frequency, t is time, Γ_m is a reflection coefficient on the surface m of the target material, and n is the number of reflections inside the material. If Γ_A and Γ_B are defined as shown in Fig. 1, (2) can be expressed as

$$r = A \cdot e^{j2\pi \cdot f \cdot (t-T)} \cdot \left(\Gamma_A + \frac{\left(1 - \Gamma_A^2\right) \cdot \Gamma_B \cdot e^{-j2\beta_1 d}}{1 + \Gamma_A \cdot \Gamma_B \cdot e^{-j2\beta_1 d}} \right) \tag{3}$$

where β_1 is the phase velocity inside the target material with thickness d. When the distance between the antenna and the target is R and

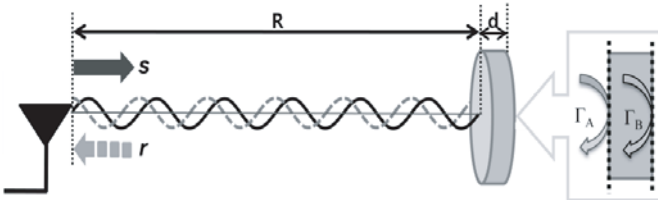

Figure 1. Conceptual diagram for comparative measurement of dielectric constants using the six-port radar sensor. — Transmitted signal (s), - - - received signal (r).

the distance-dependent term of the transmission equation ($|r/s|$) in a monostatic radar is $P_r(R)$ [10], the ratio Γ of the transmitted and received signals is written as

$$\Gamma = P_r(R) \cdot e^{-j2\beta_0 R} \cdot \left(\Gamma_A + \frac{\left(1 - \Gamma_A^2\right) \cdot \Gamma_B \cdot e^{-j2\beta_1 d}}{1 + \Gamma_A \cdot \Gamma_B \cdot e^{-j2\beta_1 d}} \right) \tag{4}$$

where β_0 is the phase velocity in the free space between the antenna and the target.

As shown in (4), the signal ratio is dependent on the target distance as well as a multiple reflection effect in the target material. As $P_r(R)$ is inversely proportional to R^4, relative comparison of the dielectric constants of the single-layer target materials can be easily obtained from accurately measured distance and signal ratios of the radar sensor. The distance measurement error, ΔR, may cause a signal ratio error, $\Delta\Gamma$, and the absolute value of $\Delta\Gamma$ is expressed as

$$|\Delta\Gamma| = \left| 1 - \left(\frac{R}{R + \Delta R} \right)^4 \right| |\Gamma| . \tag{5}$$

The signal ratios measured from the radar sensor with the six-port network agree well with the reflection coefficients of the targets if the errors from the targets at different positions relative to the antenna can be accurately calibrated and properly compensated. The six-port network can be composed of four directional couplers, one 90° delay line and RF power detectors connected to four output ports as shown in Fig. 2. The reference signal at port 1 and the received signal at port 2 are transmitted to the four output ports through the six-port network, and their phases and amplitudes are converted to output voltages by the RF diode detectors [7]. The output signals at the four output ports can be expressed as a linear combination of the reference signal and received signal. Considering phase errors in the six-port network in

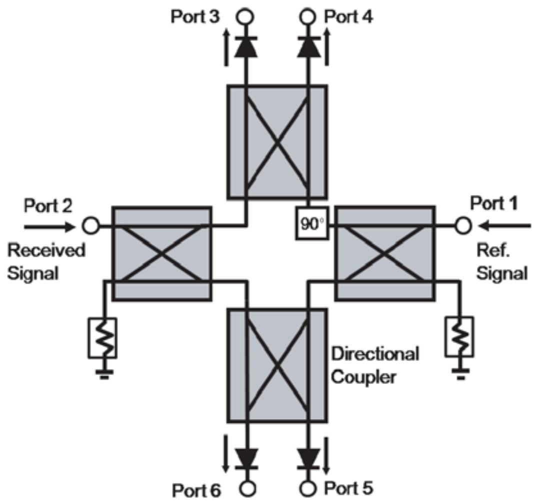

Figure 2. Block diagram of the six-port network in the radar sensor.

Ref. [11], DC output voltage V_i $(i = 3, \ldots, 6)$ of the six-port network can be expressed as

$$\begin{aligned} V_3 &= K_3 \left[1 + \alpha^2 - 2\alpha \cdot \cos(\Delta\varphi - \phi_2 - \phi_3)\right] \\ V_4 &= K_4 \left[1 + \alpha^2 + 2\alpha \cdot \cos(\Delta\varphi + \phi_2 + \phi_3)\right] \\ V_5 &= K_5 \left[1 + \alpha^2 + 2\alpha \cdot \sin(\Delta\varphi + \phi_2)\right] \\ V_6 &= K_6 \left[1 + \alpha^2 - 2\alpha \cdot \sin(\Delta\varphi - \phi_2)\right] \end{aligned} \tag{6}$$

where V_i is a diode voltage connected to the port i, K_i is a parameter including amplitude errors in the six-port network and diode mismatch effects among output ports, α is a power ratio of the reference signal and received signal, and $\Delta\varphi$ is phase difference between the reference signal and received signal, ϕ_2 is a phase error in the directional couplers connected to the output ports, and ϕ_3 is a phase error related to the 90° delay line. Using (6), the signal ratio Γ of the radar sensor is expressed as

$$\begin{aligned} \Gamma = \frac{1}{4\cos(\varphi_2)} &\left[\left(\frac{1}{\cos(\varphi_3)}\left(\frac{V_4}{K_4} - \frac{V_3}{K_3}\right) - \tan(\varphi_3)\left(\frac{V_5}{K_5} - \frac{V_6}{K_6}\right)\right)\right. \\ &\left. + j\left(\frac{V_5}{K_5} - \frac{V_6}{K_6}\right)\right]. \end{aligned} \tag{7}$$

The six-port radar sensor can compensate distance-dependent reflection coefficients very accurately because it measures the distance from phase difference between the transmitted and received signals [6, 11]. As shown in Ref. [10], the distance-dependent reflection coefficients are inversely proportional to the fourth multiplication of the distance. Therefore, the signal ratio can be expressed as

$$|\Gamma_{cal}| = |\Gamma_{meas}| \cdot \left| 1 + \frac{\Delta R}{R_{REF}} \right|^4 \tag{8}$$

where Γ_{cal} is a calibrated reflection coefficient, Γ_{meas} is a measured reflection coefficient using the radar sensor, and ΔR is the distance measurement error from the reference distance R_{REF}. The change of the signal ratio due to the distance measurement error can be compensated using (8). Although the radar sensor cannot exactly determine real values of the dielectric constants without standard targets consisting of at least three different materials, it can relatively classify the dielectric targets using distance compensation scheme from the relationship between the signal ratios and the relative dielectric constants [5, 8, 9]. Therefore, a relative comparison of the dielectric constants of the targets can be achieved with only the proposed radar sensor.

3. SENSOR ARCHITECTURE AND MEASUREMENT TARGET

The radar sensor with a six-port network is illustrated in Fig. 3. A source signal is applied using an external synthesized signal generator and is radiated through a horn antenna. A part of the radiated signal is coupled to the LO port of the six-port network. Both of the received signal and LO signal are delayed by passive elements in the six-port network, are transmitted to four diode detectors and are converted into four DC voltages. These DC voltages are processed in a signal conditioning block using low-offset operational amplifiers. The six-port network including passive elements and power detectors is implemented in an MMIC using an InGaP HBT process. The chip size is $2.0 \times 1.8\,\mathrm{mm}^2$. A quasi-circulator in Ref. [12] is used for high Tx-to-Rx isolation. The whole size of the fabricated 24 GHz six-port radar sensor module is $3.6 \times 5.5\,\mathrm{cm}^2$.

The measurement targets are prepared to demonstrate the possibility of dielectric constant distinction by the distance-compensated six-port radar sensor. The first target consists of two different dielectric constant materials and has ± 5 mm distance variation depending on the surface position, as shown in Fig. 4. The target has a rubber plate ($\varepsilon_r \approx 3.1$ in K-band) on the center of a Teflon plate ($\varepsilon_r \approx 2.1$ in K-band) and an uneven surface with no backside metal plate. In order to clearly demonstrate that the sensor can compensate the distance variation, the second target in Fig. 5 is prepared which consists of two Teflon plates with metal backsides at different positions relative to the sensor spaced 150 mm apart.

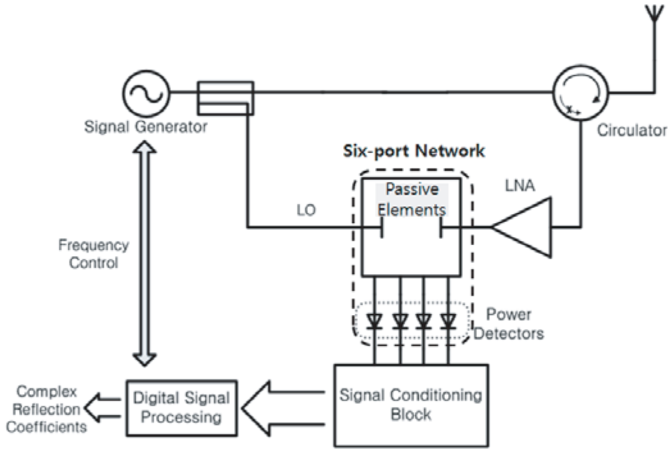

Figure 3. Block diagram of the radar sensor with the six-port network.

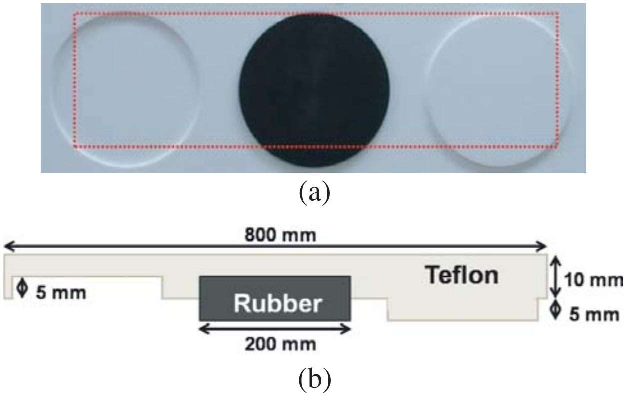

Figure 4. The first measurement target. (a) A photograph of the target and its scanned area (dotted line). (b) Physical dimensions of the target.

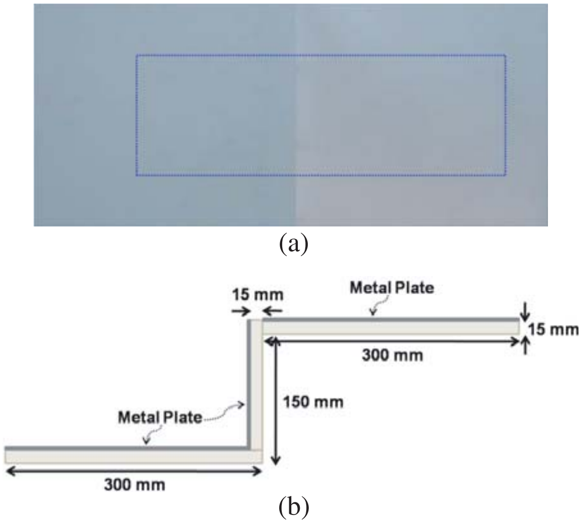

Figure 5. The second measurement target. (a) A photograph of the target and its scanned area (dotted line). (b) Physical dimensions of the target.

4. MEASUREMENT RESULTS

The measurement targets are placed at a position 0.77 m distant from the antenna on a moving rail. Figs. 4(a) and 5(a) show the scanned areas of two targets. The measured image profiles of the dielectric constants of both targets are shown in Figs. 6 and 7. In Fig. 6, the outline of the center image with 50% of contrast is similar to the edge of the rubber plate. As the image is obtained by summing and averaging signals in the entire beam width of the horn antenna, the circular boundary of the center image is slightly blurred. Therefore, in the case of an antenna with a narrower beam width or shorter distance to the target, a much clearer boundary image can be obtained. The radar sensor with the beam width below 2° can distinguish exact shapes of the targets smaller than a circle with the radius of 5 mm at 14 cm distance or less. Small distance unevenness of ±5 mm cannot be calibrated by the six-port radar sensor because the range resolution of the sensor is greater than 5 mm. However, this small variation hardly has an effect on the measurement results as shown in Fig. 6. The effect of the distance compensation is shown more clearly in the measurement of the second target. In the uncompensated image of the second target in Fig. 7(a), the target appears to have different dielectric constant materials on the left and right surfaces. However,

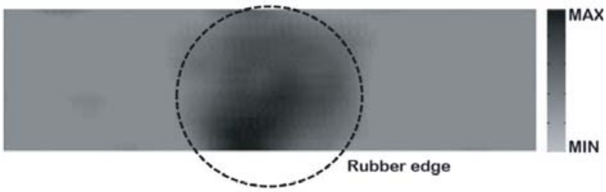

Figure 6. Measured dielectric constant profile of the first target.

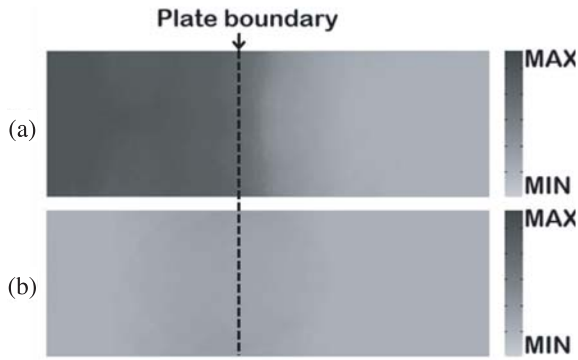

Figure 7. Measured dielectric constant profiles of the second target. (a) Uncompensated dielectric constant profile. (b) Compensated dielectric constant profile.

the compensated dielectric constant profile in Fig. 7(b) shows that the dielectric constants of the left and right plates are the same.

5. CONCLUSION

The radar sensor with the six-port network was proposed for the stand-alone measurement for relative differentiation of dielectric constants using distance compensation. The relative dielectric constants of the remote targets were easily compared from the amplitudes of the reflection coefficients which could be simply extracted from four DC output voltages and compensated by the calibrated distance in the radar sensor. Distance measurement and calibration, reflection coefficient compensation and dielectric constant comparison were simultaneously performed by the 24 GHz radar sensor. This radar sensor is expected to be in use in many applications such as industrial non-destructive detection, breast cancer detection and robot vision sensors.

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