Study on Mutual Coupling of Slot Antennas on a Stratified Medium

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1. Introduction

With the demand for quality control of exporting agricultural products, microwave sensors have been developed. For instance, a coupled-dipole sensor has been developed for moisture content measurement of paddy [1]. Both reflected and coupled signals were measured. A switched polarization coupled-dipole sensor was proposed to measure only coupled signal [2]. For fruit, a coupled-patch sensor was proposed for durian maturity stage inspection [3]. These works relied on electromagnetic simulators which require long computation time. The closed-form formulations need long time for derivation, but less time for calculation. In addition, physical insight how it works is provided. Therefore, this article presents the principle of a coupled-antenna for sensing quality of agricultural products. Calculation results are illustrated and validated by experiments which ensure the correct of the calculation. It is useful for developing a sensor for agricultural product inspection.

2. Mutual Coupling of Slot Antennas on a Stratified Medium

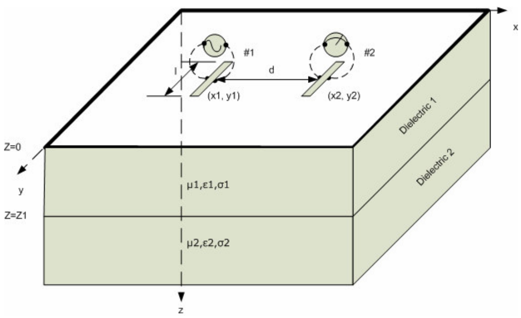


Figure 1: Geometry of the problem

Let assume two slots of length l are located on a conducting plane at z = 0 on a stratified medium. Dielectric 1, with the thickness of z_1, has constitutive parameters of ($\mu_1,\varepsilon_1,\sigma_1$) whereas the corresponding parameters of dielectric 2 are ($\mu_2,\varepsilon_2,\sigma_2$). Here, dielectric 2 has thickness of infinity for simplicity. Slot 1 is used for transmitting signal whereas slot 2 is used for receiving signal. They are located at (x_1,y_1,0) and (x_2,y_2,0), respectively. Mutual admittance of slot apertures can be expressed as [4]

$$Y_{12} = \frac{1}{V_1 V_2} \iint_{sa} \left(\vec{E}_2 \times \vec{H}_1 \right) \cdot \hat{a}_n ds' \tag{1}$$

where total electric and magnetic waves consist of incident waves to the slot ($\vec{E}_I$ and $\vec{H}_I$) and reflected waves ($\vec{E}_R$ and $\vec{H}_R$) from the dielectrics. Assume narrow slot, the magnetic current density can be represented as a cosine function. By using the spectral domain approach [5] and

Huygens's principle, electric field in spectral domain can be derived. Applying boundary conditions of continuous electric and magnetic fields at $z = 0$ and at $z = z_1$, incident, reflection and transmission coefficients are obtained. For narrow slots, the surface integral can be simplified to line integral. The stationary phase method is applied for providing analytic solution with the constraint that distance from the antenna should be sufficiently large.

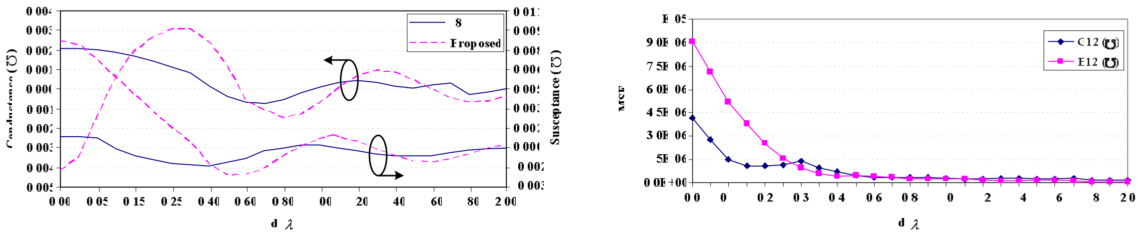
The derivation was elaborated in [6]. Once mutual and self admittances are obtained, scattering parameters can be found from [7]. From the derived expressions, coupled-slot antennas can be investigated simply and quickly. Variation of dielectric property can exhibit behavior of agricultural product.

3. Calculation Results

This section illustrates some calculation results that exhibit the usefulness of the method.

3.1 Validation

To ensure that the calculation is accurate, mutual coupling between slot antennas was compared to the results calculated in free space [8]. The mutual coupling between dipole antennas, transformed to slot antennas by using Babinet's principle, was used as a reference data. When the proposed calculation was applied to the case of free space, $z_1 \to \infty$, the resultant conductance (G) and susceptance (B) are shown in Fig.2. They are quite different when d is small and approaches the same value for the large value of d. The mean square error (MSE) of G and B are also shown in Fig.2. It is obvious that MSE approaches zero as d is larger than 0.5λ. This distance is recommended for accurate measurement results.



(a) (b)

Figure 2: Comparison of the proposed calculation of mutual admittance to the results in free space.

3.2 Variation of d and z_1

To exhibit the capability for analyzing stratified medium and possibility to detect variation of concealed object, this subsection shows variation of mutual admittance as a function of d and z_1 for a fixed value of ε_r' and ε_r''. Fig.3 shows mutual admittance at 2.45 GHz for $z_1 = 2.44cm$, $z_2 = \infty$, $\varepsilon_{r1}' = 4, \varepsilon_{r1}'' = 0.04$, $\varepsilon_{r2}' = 60, \varepsilon_{r2}'' = 15$. The slot separation d is varied between 0-12.2 cm. It is relevant that mutual admittance changes as d is changed. It may be possible to determine the object by measuring mutual admittance at various positions.

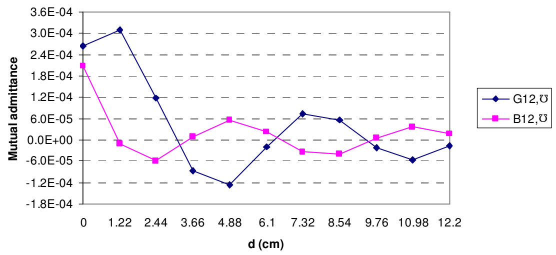


Figure 3: Variation of d

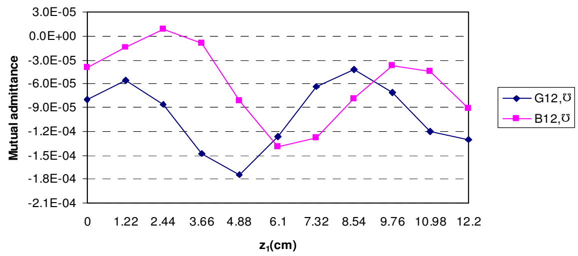


Figure 4: Variation of z_1

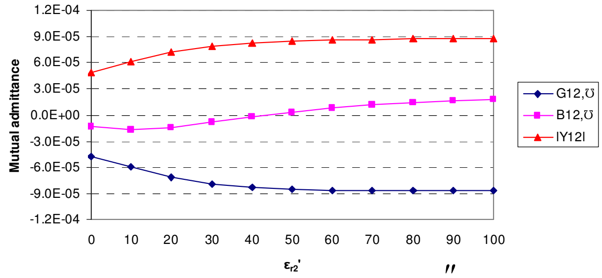
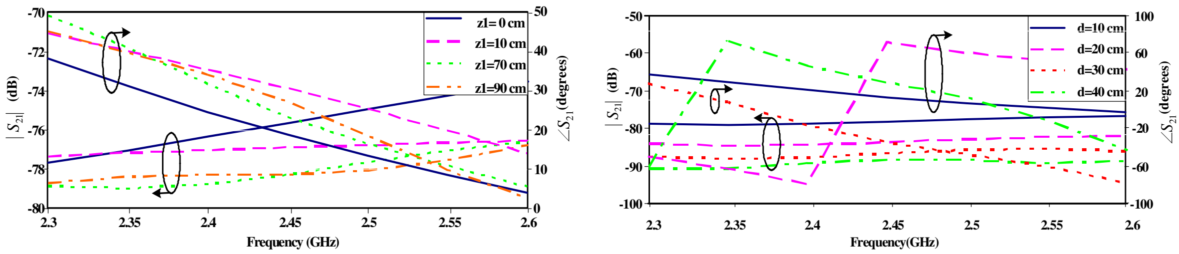


Figure 5: Variation of ε_{r2}''

The variation of z_1 when $d = 3.66cm$ is shown in Fig.4 where it exhibits the mutual admittance varies at different plane from the slots. The variation of ε_{r2}' for the case F = 2.45 GHz, $\varepsilon_{r1}' = 4, \varepsilon_{r1}'' = 0.04$, ε_{r2}' is varied, $\varepsilon_{r2}'' = 15$, $d = 3.66cm$ and $z_1 = 2.44cm$ is shown in Fig.5. It is noted that when ε_{r2}' is in excess of 40, variation of magnitude of mutual admittance is not changed. Therefore, we can observe variation of concealed object when ε_{r2}' is not so large.

3.3 Frequency response

Frequency response is illustrated for the paddy with moisture content of 12.2%. The respective ε_r' and ε_r'' are 2.39 and 0.28. At d =10 cm, variation of $|S_{21}|$ and $\angle S_{21}$ at different z_1 of 0, 10, 70 and 90 cm are shown between the frequency of 2.3-2.6 GHz in Fig.6. The $|S_{21}|$ increases along the frequency whereas $\angle S_{21}$ decreases due to the change in electrical size of the slot. It is observed that calculation results are not significantly changed when z_1 is in excess of 70 cm. Variation of $|S_{21}|$ and $\angle S_{21}$ between the above frequency for z_1=70 cm, when $d = 10,20,30$ and $40cm$, are also shown in Fig.6. It is noted that $|S_{21}|$ decreases as d is increased. Variation along frequency is not significant but $\angle S_{21}$ has more pronounced effect.



(a) z_1 (b) d

Figure 6: Frequency response for different z_1 and d

4. Experimental Results

To validate calculation results, a microstrip transmission line coupled slot was used for transmitting signal at 2.45 GHz whereas the other microstrip transmission line coupled slots were used for receiving signal. Each slot was 6.1cm long, 0.1 mm wide and separated by 10 cm. The slots were well matched to the 50Ω transmission line with return loss less than -10 dB. Relative measurements were conducted and comparison of calculation and measurement results were based on normalized value. When they were connected to network analyzer and calibrated, $|S_{21}|$ and $\angle S_{21}$ were measured at paddy with moisture content of 12.2% $(\varepsilon_r' = 2.39, \varepsilon_r'' = 0.28)$. Experiments were setup in two cases, i.e., varied z_1 and varied d. Comparison of normalized $|S_{21}|$ and $\angle S_{21}$ shown in Fig.7, when d was fixed at 10 cm, at different z_1 of 0, 10 and 70 cm. Marked error was observed at z_1 equals 0 cm whereas those of 10 and 70 cm are in good agreement with the error of 1.2 dB and 3^o, respectively.

When d was varied as seen in Fig.8, for z_1 equals 70 cm, variation of $|S_{21}|$ and $\angle S_{21}$ are in the same trend with some errors that can be calibrated. The accurate results are obtained when z_1 in excess of 70 cm.

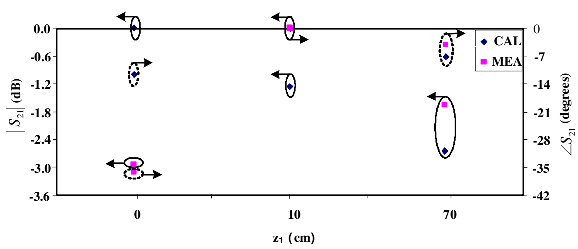


Figure 7: Measured S_{21} versus z_1

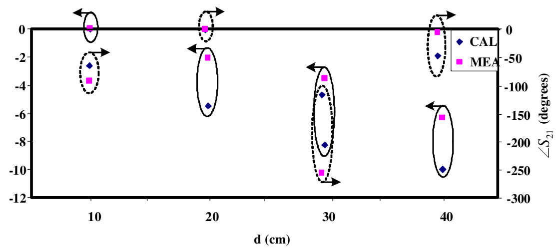


Figure 8: Measured S_{21} versus d

5. Discussion and Conclusion

Analytic solutions for mutual coupling of slot antennas on a stratified medium provide fast calculations that facilitated the investigation of an object covered or concealed by the other object. Since spectral domain approach and stationary phase method were applied, the accurate results were obtained when the calculations were conducted at 70 cm at 2.45 GHz (approximately 6 wavelength in free space). This distance is recommended for practical use, for instance, for determination of dielectric property using inverse measurement technique.

Acknowledgment

This work was supported by the Thailand Research Fund through the senior research scholar project, grant number RTA-5180002.

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