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ARTIFICIAL DIELECTRIC SUBSTRATE FOR MICROWAVE APPLICATIONS

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Abstract: *This paper presents a new version of an artificial dielectric substrate. The substrate is fabricated as a 2D array of metallic posts separated from the top conductor by a thin dielectric slab. This structure can show a very high effective permittivity. This permittivity depends on the dimensions of the posts, the permittivity of a dielectric material filling the space between the posts, and on the top dielectric slab thickness and permittivity. The thinner is this slab and the higher is its permittivity the higher is the effective permittivity. This artificial dielectric substrate is suitable for designing the microstrip line and circuits based on it. Due to the high effective permittivity, a substantial reduction in the dimensions of microwave circuit elements is possible. The simple analytical model of this structure is presented. The microstrip line on the proposed substrate was fabricated and measured. The measured and calculated effective permittivity is in a good accord. The 3 dB coupler was designed, fabricated and measured by applying the microstrip line on this artificial dielectric substrate.*

Key words: *artificial dielectric, dispersion characteristic, microstrip line, parallel plate waveguide, periodic structure*

INTRODUCTION

Artificial dielectric have been used for more than fifty years [1]. These materials are a large-scale model of actual dielectric materials. A large number of conducting particles are arranged in a regular array. Under the action of an externally applied electric field, the charges on each conducting particle are displaced and simulate the behaviour of the molecules in an ordinary dielectric. The original application of artificial dielectrics was to replace the heavy natural dielectric material in lens antennas [1]. More recently, various versions of artificial dielectrics have been used to modify the properties of materials in ways that are not attainable in nature, e.g., increasing the permittivity by a system of conducting strips [2] to design very compact high permittivity dielectric resonators. These materials can also be used to reduce the permittivity [3], even below one [4], in order to improve the radiation properties of a leaky wave antenna by a rodded artificial dielectric [4]. Artificial dielectrics are widely used for forming various artificial surfaces, e.g., high impedance surfaces [5], and antireflection coatings [6]. The surface reactance can be effectively changed by using a system of short conducting pins [7].

This paper presents an artificial dielectric material suitable for building microstrip line based circuits, Fig. 1. The material is formed by a 2D array of grounded metallic posts. A similar structure of a 2D array of grounded cylindrical pins was used in [7], but with the aim to produce a surface with a given reactance. The same idea as presented here, was used to design microstrip line based circuits in [8]. The posts are covered on their top by a very thin dielectric slab, on which the layout of the designed circuit is deposited. The substrate itself was tested in a parallel plate waveguide. Its effective permittivity was calculated by the CST Microwave Studio (MWS), and using the model of a line periodically loaded by capacitances. Effective permittivity up to several hundreds was predicted. This artificial substrate serves well as the substrate of a microstrip line that shows high effective permittivity. It can thus substitute a microstrip line on an expensive high permittivity substrate, and can substantially reduce the dimensions of the circuit.

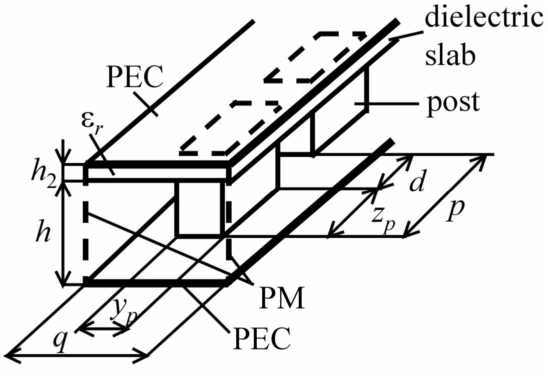
1 MODEL OF THE ARTIFICIAL DIELECTRIC MATERIAL

An artificial dielectric material can be represented by a 3D array of dipoles terminated by impedance Z_L. The periods of the array dx, dy, and dz must be considerably shorter than the wavelength, in order to be able to treat the medium as continuous. The effective length of the dipole arms is l_{eff}. The incident electric field is oriented parallel to the dipole arms. The polarization vector is defined $P = p_d / V = \alpha_e E$, where $V = dxdydz$ is the cell volume, α_e is the electric susceptibility that defines the permittivity of the medium, and p_d is the dipole electric moment. The dipole input impedance has a capacitive character with capacitance C_e. Loading the dipole by capacitor C_L we get the effective relative permittivity of this composite bulk material [8]

$$\varepsilon_{reff} = 1+\frac{\alpha_e}{\varepsilon_0} = 1+\frac{1}{V\,\varepsilon_0}\frac{l_{eff}^2 C_e C_L}{C_e + C_L} \ . \qquad (1)$$

Consequently, the medium created by the system of these dipoles shows artificially increased effective permittivity that according to (1) does not depend on frequency, supposing that l_{eff},. C_e and C_L do not depend on frequency.

Let us first study a parallel plate waveguide with the substrate made from this artificial dielectric material. The dipoles are represented by cuboidal metallic posts of dimensions y_p, z_p and h separated from the top conductor by a thin dielectric layer h_2 in thickness with permittivity ε_r, see Fig. 1a. The top and bottom conductors are represented by perfect electric (PEC) planes. Due to the periodicity of the field distribution, this infinitely wide and long structure can be analyzed as one row of posts, confined from the sides by perfect magnetic (PM) planes, Fig. 1a.



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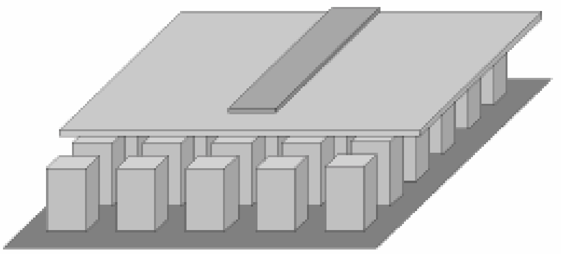

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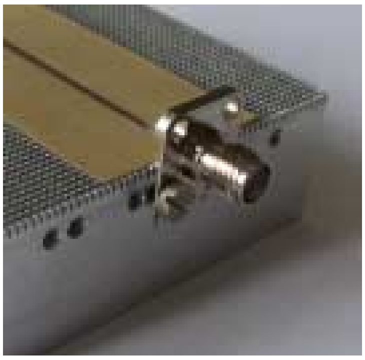

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Fig. 1: Ideal parallel plate waveguide with the artificial dielectric substrate (a). The microstrip line on the artificial dielectric substrate (b), the fabricated line with the detail of the SMA connector (c).

The line from Fig. 1a can be treated as a line periodically loaded by capacitors [9]. The dispersion equation of a bound wave on this line is [9]

$$\cos(kp) = \cos(k_0 d) - \frac{\overline{B}}{2}\sin(k_0 d) \ , \qquad (2)$$

where $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$ is the propagation constant in a free space, k is the propagation constant of a wave on the line, p is the line period, d is the space between the posts, Fig. 1a. $\overline{B}$ is the normalized susceptance of the post. This value can be roughly determined from S_{11} of the single post calculated, e.g., by CST MWS

$$\overline{B} = j\frac{2S_{11}}{S_{11}+1} \ . \qquad (3)$$

The effective permittivity of the parallel plate waveguide is defined using propagation constant k determined from (2)

$$\varepsilon_{eff} = (k/k_0)^2 \ . \qquad (4)$$

The low frequency limit of (2) gives the effective permittivity of the line defined by (4) in the form

$$\varepsilon_{eff} = \left(\frac{d}{p}\right)^2 \left(1+\frac{C_p}{C_0\, d}\right) , \qquad (5)$$

where C_0 is the capacitance per unit length of the line without the posts q in width

$$C_0 = \varepsilon_0 q \frac{\varepsilon_r}{\varepsilon_r h + h_2} \ . \qquad (6)$$

C_p is the capacitance of the post, which can be approximated assuming a very thin dielectric slab by

$$C_p = \varepsilon_0 \varepsilon_r \frac{y_p\, z_p}{h_2} \ , \qquad (7)$$

The problem in applying (4) is that in our line the posts are located rather close to each other and the susceptance (3) calculated for a single post does not give precise values. As will be shown below, this simple theory gives acceptable results for a very thin dielectric slab, i.e., for $h_2 \to 0$.

The artificial dielectric material was produced by milling from a block of aluminium which at the same time represents the grounding plane, Fig. 1c. The dimensions, Fig. 1a, are $y_p = z_p = 0.6$ mm, $d = 0.4$ mm, $h = 1$ mm, $q = 1$ mm. The dielectric slab is a plastic foil with one-sided metallization. It is $h_2 = 0.09$ mm in thickness, its permittivity is 2.9, and the copper cladding is 0.035 mm in thickness. The effective permittivity of the line from Fig. 1a is plotted in Fig. 2. It was calculated directly by CST MWS and by (4). The experimental values were determined from the wavelength of the standing wave, the distribution of which was measured along the edge of the parallel plate waveguide with the top conductor 40 mm in width. The estimation of the effective permittivity by (4) is not precise in this case. Fig. 3 shows the effective permittivity of the line from Fig. 1a, where the dielectric layer is 10 µm in thickness and permittivity $\varepsilon_r = 2$. Equation (4) now offers a better estimate of the effective permittivity. The effective permittivity increases with decreasing thickness of the dielectric layer, due to the increase in C_p. For $h_2 = 1$ µm and $\varepsilon_r = 2$ we get, using (4) at low frequencies, $\varepsilon_{eff} = 288$, now well determined by (5-7). In contrast to the ideal case of a volume material (1), the effective permittivity of the line depends on the frequency, as the behaviour of the post is frequency dependent.

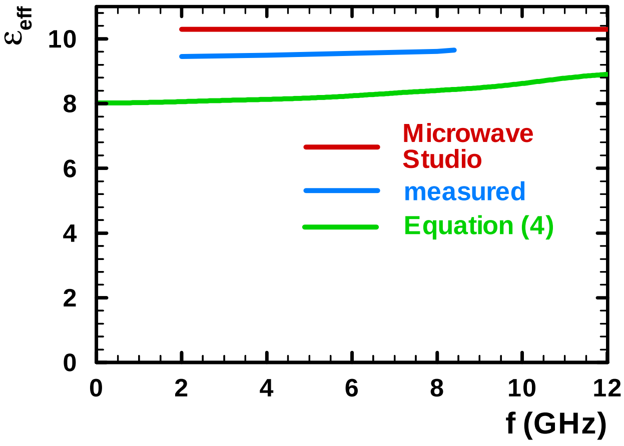


Fig. 2: The effective permittivity of the line from Fig. 1a.

2 MICROSTRIP LINE ON AN ARTIFICIAL DIELECTRIC SUBSTRATE

The proposed substrate was applied for a microstrip line. The CST MWS model of this line is shown in Fig. 1b. The microstrip line was designed and fabricated using the substrate defined above, Fig. 1c. The dielectric slab is $h_2 = 0.09$ mm in thickness, 25 mm totally in width, and its permittivity is 2.9. The microstrip line was fed via the SMA connectors as shown in Fig. 1c. The phase constant of the bound wave propagating along this line with a strip 1.2 mm in width was calculated by CST MWS and determined from the wavelength of the standing wave, the distribution of which was measured along the line. Fig. 4 shows this phase constant recalculated to the line effective permittivity. The measured data fits the calculated effective permittivity of the line well.

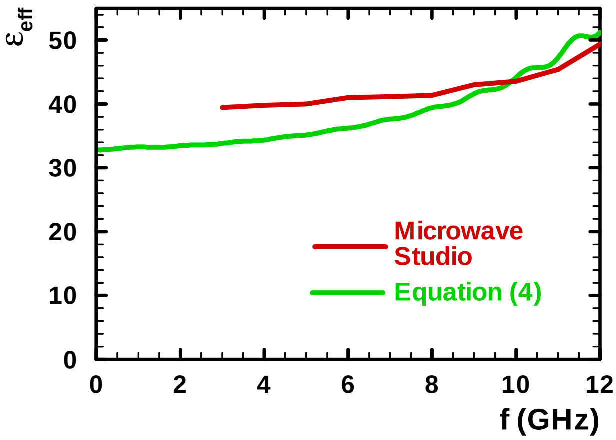


Fig. 3: Effective permittivity of the line from Fig. 1a with $h_2 = 10$ µm and $\varepsilon_r = 2$, other parameters are stated in the text.

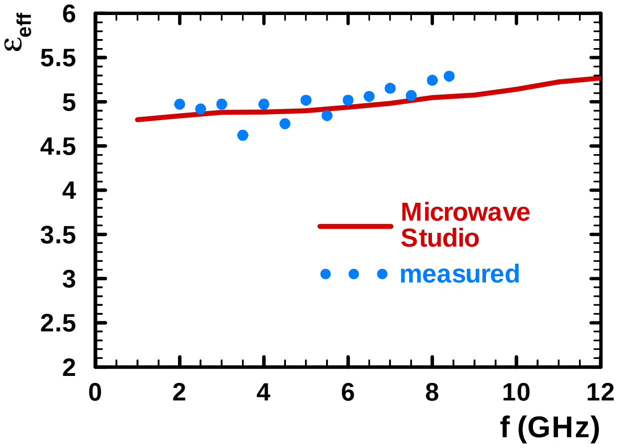


Fig. 4: Effective permittivity of the microstrip line on the artificial dielectric substrate from Fig. 1b with strip 1.2 mm in width.

The characteristic impedance of the microstrip line calculated by the CST Microwave Studio for various strip widths w is shown in Fig. 5. In Fig. 5 this impedance is compared with the calculated impedance of the microstrip line on a homogeneous solid dielectric substrate h+h_2=1.09 mm in thickness, the permittivity of which ε_r, see Fig. 5, was designed to get the microstrip line of the same effective permittivity as the line on the artificial substrate.

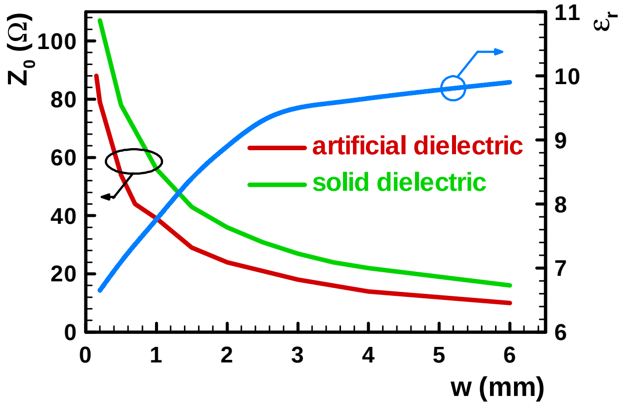
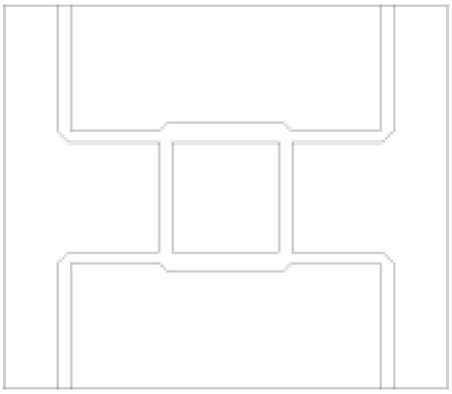


Fig. 5: Characteristic impedance of the microstrip line from Fig. 1b calculated by CST MWS at frequency 3 GHz. The relative permittivity of the solid dielectric substrate and the characteristic impedance of the microstrip line on this substrate (see the text).

3 HYBRID COUPLER

The above-described microstrip line can be used where it is beneficial to decrease the wavelength and in this way to reduce dimensions of a circuit. A 3 db hybrid coupler serves as an example of such a circuit. The arms of this coupler, see Fig. 6a, must be a quarter of a wavelength long and the impedance of the horizontal lines must be $Z_0/\sqrt{2}$ [11]. The layout of the standard coupler version, which uses the homogeneous substrate, is shown in Fig. 6a. The coupler was designed for frequency 2.4 GHz and fabricated on a substrate 0.813 mm in thickness with permittivity 3.38. The scattering parameters of this coupler, measured and calculated by the CST Microwave Studio, are plotted in Fig. 7.



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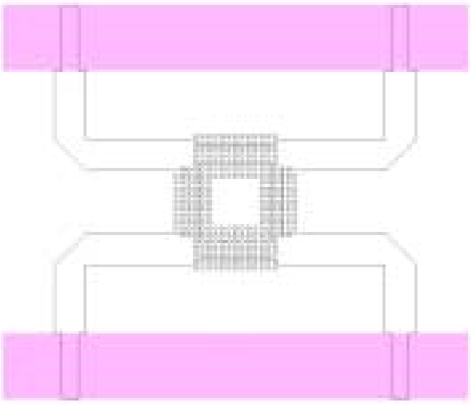

b

Fig. 6 Layouts of the couplers. The coupler on the standard homogeneous substrate (a), the structure of the coupler on the substrate with the artificial dielectric which uses the metallic cylinders (b).

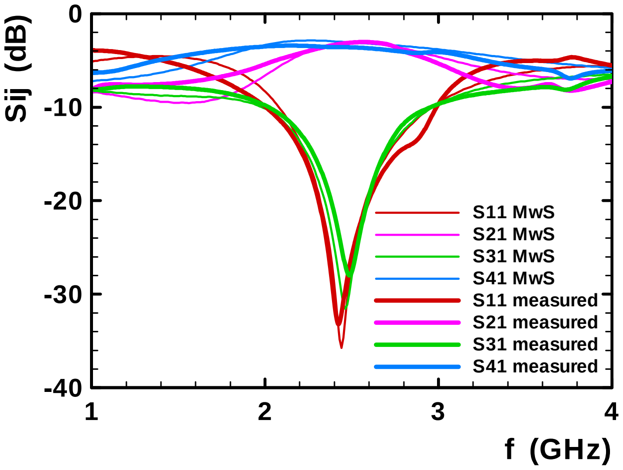

Fig. 7 Scattering parameters measured and calculated by the CST Microwave Studio of the coupler from Fig. 6a.

Fig. 6b shows the Microwave Studio model of the 3 dB coupler designed by applying the microstrip line on the artificial dielectric substrate. The substrate uses an artificial dielectric with cylindrical posts of radius 0.3 mm, length 0.813 mm, spatial period 1 mm located in air, and the top dielectric layer 0.085 mm in thickness with permittivity 2. The relative effective permittivity of the parallel plate waveguide using this substrate is 7.26. This value was calculated by the Microwave Studio and is nearly constant in the frequency band from 1 to 10 GHz. To minimize the number of applied cylinders they are placed only under the area of the coupler arms. The scattering parameters of this coupler, measured and calculated by the CST Microwave Studio, are plotted in Fig. 8.

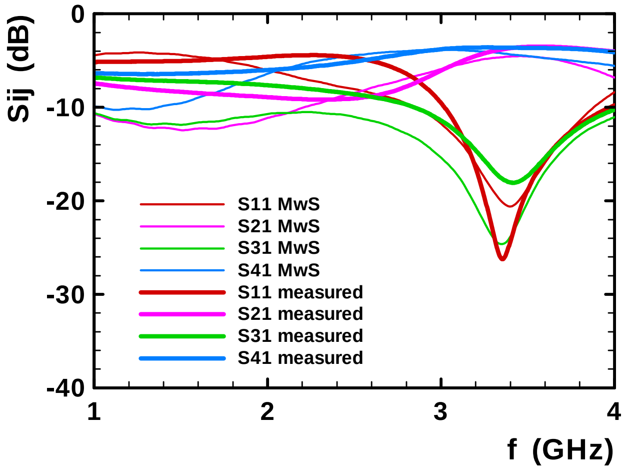

Fig. 8 Scattering parameters measured and calculated by the CST Microwave Studio of the coupler from Fig. 14c.

4 CONCLUSION

An artificial dielectric substrate is proposed in this paper. This substrate consists of a 2D array of grounded cuboidal metallic posts on top of which a thin dielectric slab is placed. This substrate is a high permittivity medium. It was tested as the substrate of a parallel plate waveguide. The effective permittivity of this waveguide can reach values up to several hundreds, depending on the dimensions of the posts, the thickness and the permittivity of the dielectric slab. This substrate is suitable for microstrip line based circuits. The microstrip line on an artificial substrate behaves similarly as a standard microstrip line on a homogeneous dielectric substrate. A microstrip line on an artificial dielectric substrate was fabricated. The measured effective permittivity corresponds well to the data calculated by CST MWS. The characteristic impedance of this line was calculated.

Two 3 dB couplers were designed, fabricated and measured to show a possible application of the artificial dielectric substrate where the shortened wavelength can be used to reduce the area occupied by a circuit. The first coupler was built as a reference circuit, using standard microstrip line technology. In the case of the second coupler the artificial dielectric substrate with cylindrical posts was used. The measured scattering parameters of the fabricated couplers fit with a sufficient accuracy the values calculated by the CST Microwave Studio.

The proposed artificial dielectric substrate itself, and the microstrip line designed on it, are suitable building blocks for microwave circuits. Due to the high effective permittivity, they can substantially reduce the dimensions of circuits such as resonators, filters and couplers.

5 ACKNOWLEDGEMENT

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