Coplanar Waveguide Short-Gap Resonator for Medical Applications

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Abstract —A coplanar waveguide short-gap resonator as an electromagnetic energy coupler for medical applications is described. The principles and design formulas are given and the experimental results for a pair of the couplers designed to operate at 915 MHz are provided. From the data obtained on a phantom, it can be shown that the coupling efficiency of this coupler is at least 3 dB better, compared with the other kinds of coplanar waveguide couplers.

I. Introduction

In recent years, an increased interest in applications of electromagnetic techniques for medical diagnostics and therapy has been observed. Among several factors for such applications, one of the most important for success is the design of EM energy couplers to efficiently couple the EM energy into tissue. Various kinds of EM couplers have been reported [1]–[4] and briefly reviewed in [1]. In general, characteristics of EM energy couplers should include high coupling efficiency, good impedance matching, minimum leakage, and convenience for clinical applications, such as light weight and the capability of conforming to the shape of the body. A coplanar waveguide (CPW), whose theory and design were reported in [5] and [6], has the properties mentioned above and offers a potential to obtain better characteristics. Based on the theory of CPW, a new CPW short-gap resonator as a coupler is proposed and basic design formulas are given. Experimental results of the couplers at 915 MHz, including impedance matching, relative coupling efficiency, and leakage obtained on a phantom, are provided.

II. Design Principles

One of the most important properties of CPW is to guide microwave energy within desired circuits [6]. In order to develop a CPW EM energy coupler to efficiently couple EM energy into a dielectric material such as tissue, there are several possibilities, including a CPW transmission-line (CPW TL) coupler terminated in a resistor, a $(3/4)\lambda_g$-length end-shorted transmission-line coupler, regular CPW cavities ($l=(1/2)\lambda_g, \lambda_g$), and short-gap cavities ($(1/4)\lambda_g$, $(3/4)\lambda_g$, and $(5/4)\lambda_g$). After all of them were tried, a short-gap cavity was found to be the best.

For a section of CPW TL as a coupler, there is a terminal resistor (50 Ω) at the end of the coupler. Therefore, the reflection coefficient of the coupler is small. On the other hand, despite the fact that when the loss tangent of dielectric material such as tissue is large, CPW TL has high attenuation, and there still is some energy dissipated in the terminal resistor. Therefore, the coupling efficiency of the coupler is not so high. For CPW regular cavities, there are no resistors. By adjusting the length of cavity, low VSWR of the couplers can be obtained. But the stored electrical and magnetic energies are equal at resonance. In order to get strong electrical fields (as is the case for charged particle accelerators and klystrons), short-gap cavities are used.

A short-gap cavity shown in Fig. 1(a) may be considered to be a section of a CPW TL L terminated in a gap G (leading to the equivalent circuit of Fig. 1(b)) provided that the gap region G is small compared with wavelength. The gap capacitance is much larger than the capacitance elsewhere in the cavity. Therefore, for a given amount of stored energy, the electric energy in the resonator should be stored mainly across the gap.

From the equivalent circuit of the short-gap cavity, the transcendental equation can be written [7]

$$jZ_0 \tan \beta l + \frac{1}{j\omega C_g} = 0 \tag{1}$$

where

$\beta = 2\pi/\lambda_g$
Z_0 CPW characteristic impedance,
C_g gap capacitance,
l length of the cavity.

For this transcendental equation, there are various solutions. When f, Z_0, and C_g are given, the length of cavity l can be calculated by

$$\beta l = \tan^{-1}\frac{1}{\omega Z_0 C_g} + n\pi \tag{2}$$

where $n = 0, 1, 2 \cdots$.

For $n=0$, the cavity is in the lowest resonance mode and its length l is nearly a quarter wavelength (l_0). For $n=1$, l is about $(3/4)\lambda_g(l_1)$, and for $n=2$, l is about $(5/4)\lambda_g(l_2)$, as shown in Fig. 2.

The characteristic impedance of CPW is

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \cdot \frac{K'(k)}{2K(k)} \Big/ \sqrt{(\epsilon_{r_1}+1)(\epsilon_{r_2}+1)} \tag{3}$$

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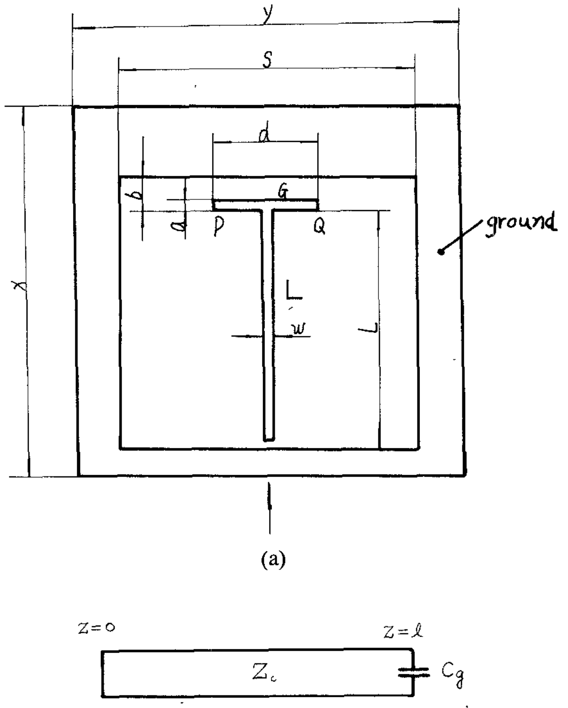

Fig. 1. (a) Coplanar waveguide short-gap cavity. (b) Its equivalent circuit.

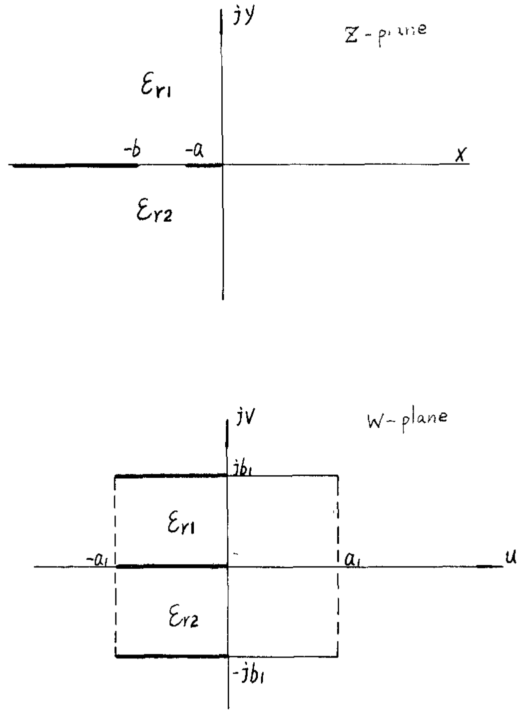

Fig. 3. Conformal mapping of NCL into W plane.

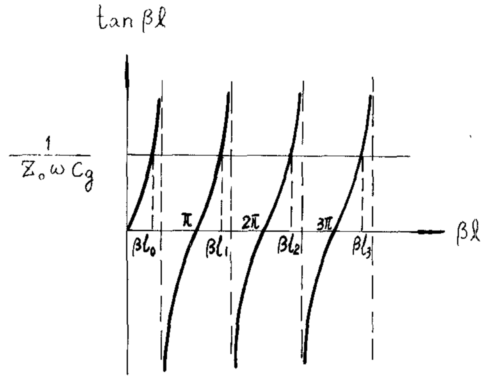

Fig. 2. Solution of (2).

where $K(k)$ = complete elliptical integral of the first kind,

$$K'(k)=K(k'),\qquad k=\frac{w}{s},\qquad k'=(1-k^2)^{1/2}.$$

So the dimensions of CPW, w and s, can be calculated.

To calculate the gap capacitance C_g, the strip PQ and ground plane of the gap region can be simplified to a nonsymmetrical coplanar line (NCL), as shown in Fig. 3 (a) [8]. If we assume the propagation of a TEM wave, NCL may be analyzed by conformal mapping, as shown in Fig. 3(b). In this case, the capacitance per unit length of NCL can be written as

$$C=(\epsilon_{r_1}+\epsilon_{r_2})\cdot\epsilon_0\cdot\frac{a_1}{b_1} \tag{4}$$

where

$$\frac{a_1}{b_1}=\frac{K(k)}{K'(k)},\qquad k=\frac{a}{b}.$$

The gap capacitance is

$$C_g=C\cdot d \tag{5}$$

where d is the length of strip PQ.

Usually the width of strip PQ, a, is chosen to be equal to the width of the center strip of resonator w. The width of gap $(a-b)$ should be small compared with wavelength, so that the coupler can be considered as a short-gap resonator. After the dimensions a and b are chosen, the gap capacitance C_g can be calculated using (4) and (5). Since the width of the gap is small, its fringing capacitance can be neglected. The length of strip PQ, d, can be adjusted to change the gap capacitance.

III. Experimental Results

Experimental CPW short-gap resonators as couplers are designed to couple EM energy ($f=915$ MHz) into tissue, i.e., $\epsilon_{r_1}=1$ (air), $\epsilon_{r_2}=56$ (tissue). For (2), $n=1$ is chosen, i.e., the length of the cavity is about $(3/4)\lambda_g$. The gap capacitance is 2.5 pf. The other dimensions of the coupler are: $s=3.32$ cm, $w=0.1$ cm, $l=2.8$ cm, $d=1.2$ cm, $a=0.1$ cm, and $b=0.3$ cm. Its thickness and dimensions of ground plane are not critical. The 3.5-mm coaxial line is used as the feeder. Its inner conductor is connected with the center strip of the coupler, and the outer conductor with the ground.

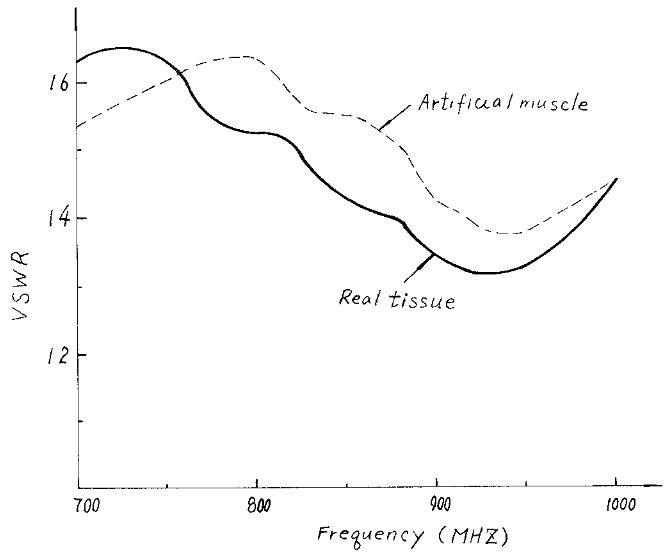

Fig. 4. VSWR's of the coupler versus frequency.

The coupler is tested by measuring the electrical-field components radiated into artificial muscle. The data show that although electric fields along the center conductor decrease rapidly, the gap causes the axial component of the electric field at the gap region to be about the same as that at the center of the coupler. Therefore, the distribution of the electric field along the coupler is relatively homogeneous.

Because of the reflection, the power into the coupler is partially reflected. Then, most of the net power into the coupler is radiated into the tissue, whereas some is radiated into the air, forming the leakage. The coupling efficiency of the coupler depends fundamentally on its reflection coefficient and the ratio of the net power radiated into the tissue to the leakage. The VSWR's for the coupler facing both artificial muscle and real tissue are shown in Fig. 4. The coupler was found to be well matched in a relatively broad range of frequencies. In practice, it is not easy to verify the coupling efficiency and leakage of the coupler. So an experiment to measure transmission through a human torso phantom was conducted with a pair of the couplers. One coupler was used as a transmission coupler, another as a receiving coupler. For the same human torso phantom, the transmission measurement is repeated with different kinds of CPW couplers. In this way, the comparison of coupling efficiencies can be made for different kinds of CPW couplers, such as a CPW TL coupler terminated in a resistor, and a CPW $(3/4)\lambda_g$-length end-shorted transmission-line coupler, etc. Because of the high attenuation of the human torso, the signal detected by the receiving coupler was comprised of two parts: one part from inside the phantom, carrying physiological information; another part from leakage waves which obscure the useful information. The larger the ratio of the part of the signal from inside the body to the part from the leakage waves, the more stable the measurement of transmission from the torso phantom, and the more the physiological information detected by the receiving coupler from inside the body. The measurements of the attenuation of the phantom showed it to be at least 6 dB lower, using these couplers, than using other kinds of CPW couplers. And the measurements with these couplers are more stable. This means that the coupling efficiency of this coupler is at least 3 dB better than that of other CPW couplers. This fact supports the previously mentioned reason for the use of a short-gap resonator.

IV. Conclusions

The design formulas and experimental results of a CPW short-gap resonator for medical applications are given. The experimental results obtained on the phantom are encouraging. The results clearly demonstrated that the coupler has high coupling efficiency and minimum leakage radiation. Concurrently, the coupler has the advantage of being small, light weight, and capable of conforming to the shape of the body. Although the coupler was designed and tested at 915 MHz, using the formulas in this paper, resonators operating at other frequencies for medical applications can be designed.

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Y. X. Wang, photograph and biography unavailable at the time of publication.