The influence of bulk conductivity on Lorentz force generated by coplanar waveguide

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Abstract. Lorentz force has been used to modify the boundary layer around the controlled body. The Coplanar Waveguide (CPW) structure can support a quasi-TEM (Transverse Electromagnetic) mode of low frequency microwave propagation. Meanwhile the Lorentz force could be induced by electric and magnetic fields in the cross section. But the force is deeply influenced by the fluid bulk conductivity. Therefore, in this paper, particular emphasis is placed on exploring the effect of varying bulk conductivity on the Lorentz force. The results show that the microwave attenuation increases very rapidly with the increase of frequency and bulk conductivity. Moreover, the strength of Lorentz force is increased with the bulk conductivity over 0~1 s^{-1}.

1. Introduction
The researchers in different countries developed many new propulsion tools and fundamental theory of propulsion physics [1, 2]. And the Lorentz force was employed to boundary layer control and propulsion, successfully in the last few years, and attracted new attention again due to its potential engineering application background. With the use of the electromagnetic actuators covered on the object surface, Lorentz force distribution, noise suppression, drag force reduction, vibration absorption and noise suppression have been investigated widely [3-5].

In addition to the actuators, more new style methods have been discussed. The CPW structure can support a quasi-TEM mode of low frequency microwave propagation. Meanwhile electric and magnetic fields can be generated in the cross section. And the Lorentz force along the coplanar waveguide circuits can be induced by the mutual interaction of the double fields.

In this paper, we mainly discuss the distributions of electric, magnetic and Lorentz force fields around the CPW, immersed in flow field with different bulk conductivities [6]. In order to improve the propulsion efficiency more effectively, the influence of bulk conductivities on Lorentz force will be mainly discussed.

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2. Theoretical Model

2.1. The design of CPW circuit

A common CPW on a dielectric substrate consisted of a center strip conductor with semi-infinite ground planes on either side is shown in figure 1. The \( L \) is the length of CPW, \( W \) is width of center strip conductor, \( D1 \) is the slot width, \( D2 \) is the width of ground planes, \( T \) and \( H \) is the thickness of double side and lower ground planes, respectively.

![Figure 1. Schematic illustration of coplanar waveguide.](image)

In this simulation we set \( W = 1.5 \) mm, \( T = 0.035 \) mm, \( H = 7 \) mm, \( D1 = 1 \) mm, \( D2 = 13.28 \) mm and \( L = 100 \) mm, respectively. During the microwave propagation, many losses will be generated, in which Ohmic loss is predominant, which is mainly induced by the unperfected medium material. So the linear uniformity materials of CPW should be used. In order to avoid the radiation loss and keep the quasi-TEM mode, silver (Ag) and GaAs are the excellent materials using as the material of strip and ground planes, respectively.

2.2. The propagation characters

The CPW structure can support a quasi-TEM mode of low frequency microwave propagation. Meanwhile electric and magnetic fields can be induced in the cross section, as shown in figure 2.

![Figure 2. The field intensity distribution graph in the cross section ((a) electric field, (b) magnetic field).](image)

Figure 2(a) and (b) illustrate the distributions of electric field and magnetic field, respectively, in the cross section of coplanar waveguide. It is observed that the electric-field lines extend across the slot while the magnetic-field lines are perpendicular to the fluid-dielectric interface in the slot. The electric field structure in the figure 2(a) is in the opposite direction of the magnetic field structure in the figure 2b. So the Lorentz force is induced along the slot [7].

3. Theoretical Model

The vector wave equations of electromagnetic field are

\[
\nabla \times \left( \frac{1}{\mu_r} \nabla \times \mathbf{E} \right) - k_0^2 \varepsilon_r \mathbf{E} = 0
\]

(1)

\[
\nabla \times \left( \frac{1}{\varepsilon_r} \nabla \times \mathbf{H} \right) - k_0^2 \mu_r \mathbf{H} = 0
\]

(2)

where \( \varepsilon_r \) is relative dielectric constant, \( \mu_r \) is relative permeability, \( k_0 \) is the wave number in free space, \( \mathbf{E} \) is the electrical field strength and \( \mathbf{H} \) is the magnetic field strength in equation (1) and equation (2).
Define the Poynting vector \( S \) (or instantaneous Poynting vector \( \text{W m}^{-2} \)) as the energy flows through unit vertical section, in the direction of energy flow, during the unit time. On the other hand, the Maxwell’s equations conserve certain properties—the magnetic field strength, and the Poynting vector that describes the electric or magnetic flux of an electromagnetic field.

\[
S = E \times H \quad (3)
\]

\[
F = J \times B = \sigma(E \times B) = \sigma(E \times \mu H) = \sigma \mu S \quad (4)
\]

Here \( \mu \) and \( \sigma \) are relative permeability and electrical conductivity, \( J \) is current density, \( B \) is strength of magnetic flux, \( F \) is the strength of the Lorentz force. Due to the rapidly phase change of microwave, power density can be investigated by the average Poynting’s vector \( S_{av} \) over one period \( T \).

\[
S_{av} = \frac{1}{T} \int_{0}^{T} S dt = \text{Re}[E \times H^*] \quad (5)
\]

\[
F_{av} = \sigma \mu S_{av} \quad (6)
\]

The \( F_{av} \) denotes the force average strength over one period based on equation (6).

4. Numerical investigation

4.1. The effect of frequency

The transmission character of microwave is deeply influenced by the surrounding medium, microwave frequency (Freq) and so on. And the quasi-TEM mode propagation of microwave on a CPW has low dispersion and hence offers the potential to construct the single direction force. So during the simulation, proper frequency should be set according to the different bulk conductivity.

The S-parameters are usually used to discuss the attenuation of CPW. Figure 3 (a-d) illustrate the distributions of the return loss \( S11 \) and insertion loss \( S21 \) with \( \text{Freq} \) for \( \sigma \) is equal to 0, 0.2, 0.5 and 0.8, respectively. Where \( S11 \) is input reflection coefficient with matched output port. The \( S21 \) is forward transmission gain with matched output port (the two S-parameters are analyzed in this paper).

![Figure 3](image-url)
These figures show that for $\sigma$ equal to 0, the $S_{21}$ parameters keep almost to a parallel line, at about 0 dB. And the $S_{11}$ appears significantly reduction at several frequency points, such as 0.45 and 2.8 GHz. It is worth noting that these S-parameters at low frequencies decrease with the increase of frequency for the four cases. For CPW the larger $S_{11}$ and lower $S_{21}$ parameters denote the less loss of microwave. The analysis of frequency suggests that the low frequency microwave show less loss for CPW in the different bulk conductivity mediums and larger bulk conductivity could lead to much loss. Thus the low frequency $Freq=0.05 \text{ GHz}$ will be considered in the numerical simulation.

4.2. The influence of field strength distributions due to bulk conductivity
Figure 4 and 5 are the distribution of electric and magnetic fields for two different bulk conductivities $\sigma=0.5$ and 0.8, respectively.

![Figure 4](image1)

![Figure 5](image2)

**Figure 4.** The distributions of electric field for zero phase.

**Figure 5.** The distributions of magnetic field at zero phase.

The microwave travels with the light speed, which is about 300,000 kilometres per second. In this simulation, the rapid variation of the phase with time could be ignored, so we just consider the whole field strength is of the uniform distribution over the section (and the average value is about $1/\sqrt{2}$ of the maximum field strength). Note that, for larger bulk conductivity $0.8 \text{ s m}^{-1}$, the microwave is attenuation much more sharply over the surface of CPW and the distribution of strength field shapes like a circular truncated cone.

4.3. The math model of Lorentz force
The total force over the CPW can be obtained by the average energy density and the action volume. In order to simplify math model, in this numerical simulation, the average electric field $E_0$, magnetic
field $H_0$ and the Poynting's vector $S_{av0}$ in a vacuum, over the input port should be used as the benchmark to approximately calculate the effective energy density. And this simulation also ignores microwave heat and radiation loss. The figure 6 presents the distribution of $S_{av0}$ over the input port. And we should also assume that in microwave radiation zone of the same energy volume density as the face density of the input port $S_{av0}$. The figure 6 is the distribution of $S_{av0}$ over the input port and it presents that the strength of $S_{av0}$ is decreasing with the increase of the distance to the center strip conductor. The average radius $R$ is 6 mm and $S_{av0}$ is $0.8 \times 10^4$ (W m$^{-2}$).

$$S_{av0} = \frac{1}{T} \int_0^T S dt = \text{Re} \left[ E_0 \times H_0^* \right]$$  \hspace{1cm} (7)

Figure 6. The distribution of $S_{av0}$ over the input port.

In figure 4 and 5, it is seen that strength of microwave decreases with the wall normal direction, but for larger $\sigma$ and longer distance to the input port, the amplitude of electric and magnetic fields decreases significantly. Here a math model is used to investigate the propagation characteristics of Lorentz force. Based on the field structure characteristics, the input port over the CPW could be seemed as a semi-circle (the radius $R$ is approximately equals to the average microwave amplitude of the input port) as well as the output port (the radius $r$). Here we only discuss the $S21$, based on its basis definition the relationships could be written as:

$$S21 = 10 \log_{10} \left[ \left( \frac{A_{out}}{A_{in}} \right) \right]^2 \approx 10 \log_{10} \left( \frac{r}{R} \right)^2$$  \hspace{1cm} (8)

Where $A_{out}$ and $A_{in}$ denote the average microwave amplitude of output and input, respectively. And the volume of circular truncated cone could be calculated based on the long of CPW, the radius $R$ and $r$. Figure 7 presents the body of circular truncated cone denotes the control zone of the force.

Figure 7. The diagram model of the microwave distribution.

The effects of bulk conductivity $\sigma$ on the computed action range $V/2$ and strength $F$ of Lorentz force at a fixed frequency of 0.05 GHz are shown in figure 8 and 9. As expected, the action region space of microwave attenuation increases very rapidly with the increase of the bulk conductivity $\sigma$. 

5
The figures 8 and 9 also show that $V/2$ is $2.7 \times 10^{-6}$ m$^3$ and $F$ is 0 N while $\sigma$ is 0 s m$^{-1}$. And when $\sigma$ is equal to 0.2 s m$^{-1}$, there is about 30 percent decrease in the microwave radiation space volume ($V/2$) comparing with the case of $\sigma=0$ s m$^{-1}$. It is important to note that the Lorentz force $F$ is not depended on the action region space $V$. This is due to the fact that in addition to the loss introduced by the increasing of $\sigma$, the strength of Lorentz force is also proportional to $\sigma$ in the equation 3. In general, for $\sigma$ over the range of 0 and 1, the Lorentz force generated by CPW is increasing along with the bulk conductivity. It is clear from the above discussion that active control methods present an attractive alternative to the current methods used in micro-propulsion.

5. Conclusions
(1) The CPW structure can support a quasi-TEM mode of low frequency microwave propagation. And the Lorentz force along the CPW direction can be created by mutual coupling of landscape orientation electric and magnetic fields. (2) The attenuation increases very rapidly with the increase of frequency and bulk conductivity. (3) The strength of Lorentz force is increased with the bulk conductivity over 0–1 s m$^{-1}$.

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