The Ring-Shape Antenna Modelling and Diffraction Measurements

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Abstract: *Existence of Gaussian electromagnetic beams in magnetized solid-state plasma provides the possibility for modelling the ring – shaped antenna with the dimensions much smaller (~20 times) than the real object. The direction diagram and the angle of diffraction in this case may be measured in laboratory instead of field works.*

1. Introduction

The experimental measurements of direction diagram and angle of diffraction of the ring-shape antenna is very complicated and expensive procedure. If the antenna is placed in ionosphere (satellites, aircraft) the measurements are completely impossible. In such cases it is convenient to use antenna modelling by the help of helicon beams in solid state plasma. Helicon waves will propagate in metals, semiconductors when a magnetic field is applied. They have an exact analogy with whistler wave which is frequently propagated in the rarefied plasma of the Earth's ionosphere. It means that the properties of ionosphere can be duplicated in magnetized semiconductors.

Antenna's dimensions are of the order of wave length λ. For example, if the wave frequency f = 100 MHz in the ionosphere we have λ = 300 cm whereas in the magnetized semiconductor λ = 1 mm, and experimental investigation of the direction diagram and diffraction in the nearest zone $L \approx 10\lambda$ offers no difficulty.

2. Subject and method of investigation

The experimental arrangement of a ring-shaped antenna for exciting and detecting of channeled electromagnetic waves in a solid-state plasma is shown in Fig. 1.

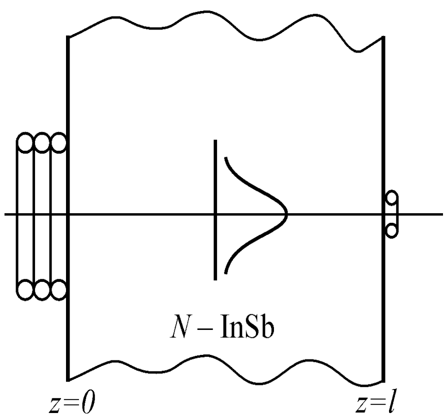

Fig. 1. Experimental arrangement.

A plane ring-shaped excitation coil (antenna's model) is applied to the surface of a semiconductor plate at $z = 0$. Also shown in Fig. 1 is the profile of Gaussian beam $U(r)$. At the opposite surface of the plate, at $z = l$, there is the pickup turn of much smaller diameter; by moving this pickup we can record the radial profile $U(r)$ at both $z = 0$ and $z = l$. At a low beam intensity, diffraction causes a broadening of the beam with increasing intensity, the diffraction angle decreases. We attribute this contraction of the channelled beam to self-focusing. The distribution of the high-frequency magnetic and electric fields may be represented as a sum of Gaussian radial functions. The field distribution and diffraction of magnetoplasma beams may be find from equation of motion [1]

$$\tau^{-1}\boldsymbol{j} + (e/mc)\boldsymbol{j} \times \boldsymbol{H}_0 = (Ne^2/m)\boldsymbol{E} \qquad (1)$$

and Maxwell's equations

$$\nabla \times \boldsymbol{E} = i\omega\,\boldsymbol{H}/c\,;$$

$$\nabla \times \boldsymbol{H} = 4\pi\,\boldsymbol{j}\,/c\,; \qquad (2)$$

$$\nabla \cdot \boldsymbol{H} = 0,$$

where e, m, τ, N are the charge, mass, relaxation time and density of the electrons, ω - angular frequency. $\boldsymbol{j}$, $\boldsymbol{E}$ and $\boldsymbol{H}$ are vectors of current, electrical and magnetic fields, $\boldsymbol{H}_0$ - vector of the constant magnetic field along the axis z. The time dependence is supposed to be in the form exp - ωt.

By the operation $(\partial/\partial z)\nabla\times\nabla\times$ applied to equation (1) in accordance with Maxwell's equation (2) we obtain

$$(\partial^2/\partial z^2)\nabla^2\boldsymbol{H} - [(\omega\omega^2_p)/(c^2\Omega_C) -$$

$$- (i\nabla^2)/(\tau\,\Omega_C)]^2\,\boldsymbol{H} = 0, \qquad (3)$$

where

$$\Omega_C = eH_0/(mc), \quad \omega^2_p = 4\pi N e^2/m.$$

The magnetic field components H_z, H_φ and H_r in the cylindrical coordinates may be expressed in terms of single scalar function Φ:

$H_z = (\partial^4/\partial z^4)\Phi - k^4\Phi, \quad k^2 = (\omega\omega_p^2)/(c^2\Omega_C);$ (4)

$H_\varphi = - ik^2 (\partial^2/\partial z\partial r)\Phi, \; H_r = (\partial^4/\partial z^3\partial r)\Phi;$ (5)

The function Φ itself must satisfy the equation (3).
By the help of (2) we obtain also

$(\partial/\partial z)j_z = [ick^2/(4\pi)]/[(\partial^4/\partial z^4)\Phi - k^4 \Phi] =$

$= ick^2/(4\pi) H_z ;$ (6)

$j_\varphi = ck^4/(4\pi) (\partial/\partial r)\Phi,$

$j_r = [ick^2/(4\pi)][(\partial^3/\partial z^2\partial r)\Phi];$ (7)

$E_z = 0, \quad E_\varphi = - (i\omega/c) [(\partial^3/\partial z^2\partial r)\Phi],$

$E_r = (\omega k^2/c) (\partial/\partial r)\Phi.$ (8)

The solution for the scalar function Φ is sought in the form

$\Phi = U(x,y,z) \exp i(kz + ik''z),$ (9)

where $U(x,y,z)$ is a function of x, y and z that varies slowly in comparison with exp ikz. Taking $\Omega_C \tau >> 1$, we can write the wave number k and attenuation factor k'' of a helicon wave propagating in the z direction as

$k = [(\omega\omega_p^2)/(c^2\Omega_C)], \quad k'' = k/(2 \Omega_C \tau).$ (10)

Substitution of Equation (9) in Equation (3) (after the replacement $\boldsymbol{H} \to \Phi$), with the condition $\Omega_C \tau >> 1$ gives for U the approximate parabolic equation

$\partial^2U/\partial x^2 + \partial^2U/\partial y^2 + 4ik\partial U/\partial z = 0.$ (11)

Equation (11) can be solved as slightly divergent Gaussian beam in magnetoplasma [2]. For the radially symmetric modes we have

$U(x,y,z) = A (W_0/W)\exp[- i(n + 1)\mathrm{arctg}(z/kW_0^2) -$

$-(ikr^2/ R)] \cdot \exp[- (r/W)^2] L_n (2r^2/W^2),$

$r^2 = x^2 + y^2, \quad W^2(z) = W_0^2 [1+ (z/ k W_0^2)],$

$R(z) = z [1 + (k W_0^2/z)], \quad n = 0,2,4,\ldots$ (12)

where $W^2(z)$ is the half-width of the beam, $R(z)$ is the phase front curvature radius, and L_n is a Laguerre polynomial. The wave energy is concentrated in a region with radius ~ $W(z)$ and decreases gaussially away from the beam center.

At $z = 0$, there is a plane phase front $(R\to\infty)$ and a minimum width $2W_0$, which may have any value. However the field broadening beyond its narrowest part depends on this minimum width. The divergence angle at the points further from the plane $z = 0$ is given by

$\theta = 1/(kW_0) = \lambda/(2\pi W_0), \quad \lambda = 2\pi/k.$ (13)

The angular dependent modes may also be excited and investigated experimentally. In this case the wave equation (11) for the scalar function U becomes

$[\partial^2/\partial r^2+(1/r)\, \partial/\partial r +(1/r^2)\partial^2/\partial\varphi^2 + 4ik]U = 0$ (14)

and the general solution (11) comprises also Laguerre polynomials of the higher order [3].

The radial field distribution for the higher beam modes is similar to that of self-focusing channels [3]. If the surface carrying the ring-shape antenna is convex, the original distribution is compressed. The position of the focus depends on the radius of curvature of the excitation surface.

3. The measurement results

The Fig. 2 shows the radial dependences of the z, r and φ components of $\boldsymbol{E}$, $\boldsymbol{H}$ and the high-frequency current j for the principal radial mode, as given by Eqs. (4 ÷ 8) and (12) when $n = 0$. The attenuation factor may be shown to increase with the mode number n. This has been confirmed by experiment.

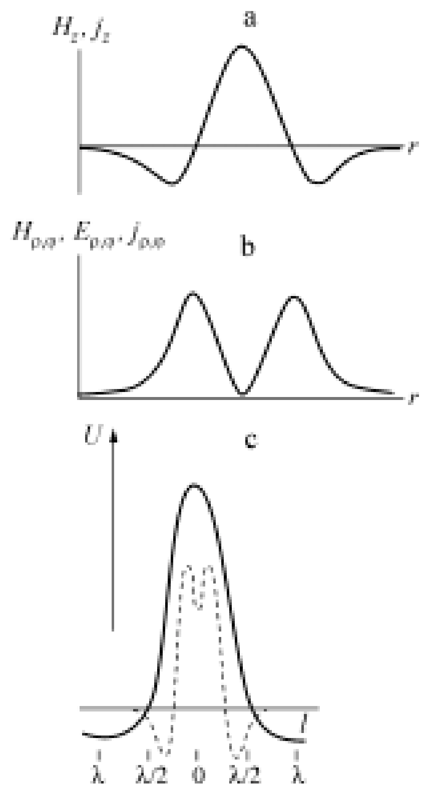

Fig. 2. Radial dependence of components of the vectors $\boldsymbol{E}$, $\boldsymbol{H}$, $\boldsymbol{j}$ for the principal radially symmetric mode (a, b); dependences of the voltage U proportional to the component H_z on the distance l expressed in half-waves (c).

The magnetoplasma Gaussian beam divergence angle was measured in indium antimonide samples having electron density N = 1.4 10^{22} m^{-3} and electron mobility μ = 7.5 m^2 V^{-1} s^{-1} [4], in the form of plates with thickness d = 15 mm at 290 K, frequency f = 300 MHz, and constant magnetic field induction B_0 = 1 T (wave length $\lambda \approx 6$ mm). The intensity distribution for the component H_z of the high-frequency magnetic field was measured with a ring-shaped antenna 1 mm in diameter placed on the further plane of the sample. Fig 2c shows the signal U transmitted by the helicon waves, as a function of the distance between transmitting and receiving antennas, expressed in half waves. The dashed curve shows the corresponding function on the plane of transmitting antenna. In Fig. 2c, the second mode (n = 2) is quite strong in the original distribution, whereas on the opposite side of the sample we have almost exclusively the principal mode (n = 0).

4. Conclusions

The proposed method for the experimental modelling and measurements of the direction diagram and angle of diffraction of the ring-shaped antenna provides and opportunity to work with the model of antenna the dimension of which are about 20 times smaller than the real object. There is shown that the electromagnetic field in the ionosphere and solid-state plasma may be described by the Gauss- Laguerre functions. The simple means of exciting and detecting of channelled electromagnetic waves in solid-state plasma allows to realize various Gaussian radiation modes of the ring-shape antenna.

References

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SUMMARY

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Gaussian electromagnetic beams in magnetized solid state plasma provide the possibility for modelling the ring-shaped antenna with the dimensions much smaller (~ 20 times) than the real object. Experimental arrangement is considered. The direction diagram and angle of diffraction in this case may be measured in laboratory instead of field works. Ill. 2, bibl. 4.