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GOTO Naohisa, “ Invention and practical uses of circular-plane radial line slot antenna（RLSA）”

Biography；

1935-6-8　Birth

1959　Graduation, Tokyo Institute of Technology

1964　Doctor of Engineering, Graduate School of Tokyo Institute of Technology

1964　Research Assistant, Tokyo Institute of Technology

1966　Associate Professor, Training Center of Tokyo Institute of Technology

1968　Associate Professor, Chiba University

1975　Associate Professor, Tokyo Institute of Technology

1980　Professor, Tokyo Institute of Technology

1996　Professor, Takushoku University

Present　Professor Emeritus, both Tokyo Institute of Technology and Takushoku University

There are many unknown formulas in my Japanese Archives. Meaning of formulas will be explained using the same pictures in Japanese Archives. At first, we consider about displacement current which is often appeared in electromagnetic waves.

The Institute of Electronics, Information and Communication Engineers consists of many research groups. Research result of student is usually presented by himself at research group (A•P), where (A•P) means (Antenna and Propagation).

After 1966 (my promotion to Associate Professor) we have meeting with respect to electromagnetic waves at research group (A・P). Several persons explain several parts of electromagnetic waves. According to my text book on electromagnetic, I explain “ displacement current ” by using a condenser which consists of two parallel conductor plates.

Between two parallel conductor plates there is electric flux density ***D***. The electric flux density is perpendicular conductor plates of condenser. Then displacement current density ***J*** is defined to be differentiation of ***D*** with respect to time *t*. Dr.Kituregawa of Mitsubisi Denki company ask me, for example, direction of ***J***. I cannot answer to his question.

The condenser of two parallel conductor plates shown in Fig.12 is the same of Fig.9.4 in “ Electricity and Magnetism ” in Berkeley Physics Course, translated into Japanese published by Maruzen Corporation. In Fig.12 of the Archives, conduction current and displacement current are shown by white and black arrows, respectively. A pair of two parallel conductor plates means radial line from center to up and down edge of circular plates.

When two parallel conductor plates consist of a condenser, displacement current flows from center to up and down edge of circular plates. In this case, from the first a pair of charge cannot be given at center of parallel conductor plates, as shown right side of Fig.12. Therefore a pair of charge, plus *q* and minus *q*, must be given outside each conductor plates of condenser.

Fig. 12

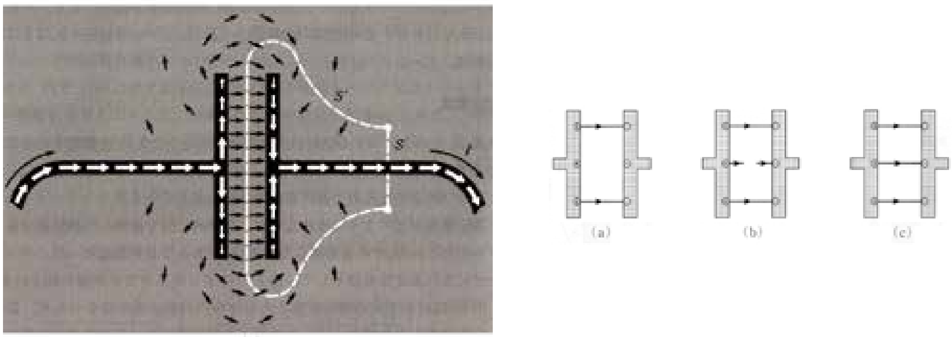
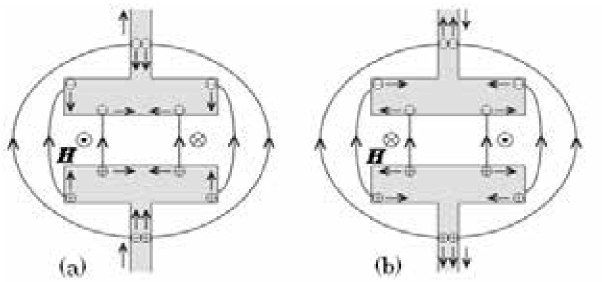


Fig.13(a) shows a condenser where Fig. 12 is rotated to left direction by 90 degrees. Current in both perpendicular conductor line flows to upper direction. However parallel conductor plates of condenser in Fig.13 is very small and thick in order to show behavior of electrons clearly.

Fig.13



In Reference [11], equations (6.1) and (6.2) are as flows

Ampere law $\boldsymbol{H} = \varepsilon \boldsymbol{v} \times \boldsymbol{E}$ (6.1) and Faraday law $\boldsymbol{E} = -\mu \boldsymbol{v} \times \boldsymbol{H}$ (6.2)

These relation between vectors are shown in (5.27) and (5.29), obtained by mutual action between electric and magnetic charges. As a result we get next formulas by using electric flux density ***D*** and magnetic flux density ***B***. formula number (1.061) depend on equation (6.1) of Reference [11].

(1.061) $\boldsymbol{H} = \boldsymbol{v} \times \boldsymbol{D}$ (1.062) $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}$

A formula (1.061) means that when a screw is rotated from ***v*** to ***D*** direction, the screw moves to ***H*** direction. Consider surface of lower conductor plate in Fig.13(a). A plus charge *q* moves to ***v*** direction, making flux density ***D*** of up direction. Consequently, magnetic field ***H*** is perpendicular to this paper sheet with up direction & . From Fig.13 and formula $\boldsymbol{H} = \boldsymbol{v} \times \boldsymbol{D}$, we can know how the displacement current flows in order to make magnetic fields.

Supplement Explanation of Japanese Archives

1. Invention of radial line slot antenna (RLSA).

The right side conductor plate of Fig.12 is assumed to be perfect circular plate without center hole. The conductor plate corresponds to brown circle of Fig.14-1. This conductor plate is the first radial line slot antenna (RLSA). The brown circle antenna is presented by M.Yamamoto (student) on August 1980 as a plane antenna of five slot pairs. Principle of RLSA will be clear by use of Fig.14. At origin of coordinates in Fig.14-2, & shows positive direction of z axis.

Fig.14-1

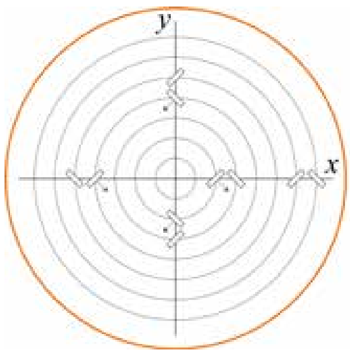
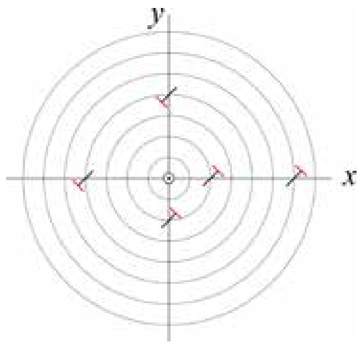


Fig.14-2



Consider only two perpendicular slot pairs, for example, on the positive x axis in Fig.14-1. Since current flow to positive x direction, two perpendicular slot pairs radiate electromagnetic waves for positive z axis direction. Interval of each circle is a quarter wave%zlength. Then peak of current is removed to next slot which radiate electric field perpendicular the next slot.

When peak of current is again removed to next slot, the first slot radiates electric field of opposite direction. We get circularly polarized wave. Since circular plain antenna is usually fed at center, the same current flows for all radial line direction. All slot pairs radiate circularly polarized waves in Fig.14-1.

The first perpendicular slot pair on positive x axis in Fig.14-1 radiates circularly polarized electromagnetic waves with rotation of left direction. This slot pair is written as shown at the position of first slot on positive x axis in Fig. 14-2. Another corresponds to slots with arrow in Fig.14-1.

2. RLSA design for はやぶさ 2

This is a problem presented by Prof. J. Hirokawa as a student. Since antenna is fed at center, current density decreases for large radius. Then slot pairs are cut on spiral line, total circular plane is fed by similar power. We can expect to get high gain circular plane antenna.

Both directions of solar battery and plane antenna are nearly equal, parabola antenna cannot be used as first はやぶさ. RLSA is suitable for circularly polarized electromagnetic waves, since high frequency can be used.

3. Electromagnetic wave form radiated by small dipole

There is small dipole on z axis at origin of orthogonal coordinates. Since this dipole radiates field shown equation (1), electric fields must be function of time t as $E_r(r, t)$ and $E_q(r, t)$ in order to express wave form. From Fig,4 next formula can be obtained

(1.1) $$\frac{\Delta r}{r\Delta\theta}=\frac{E_r(r,\ t)}{E_\theta(r,\ t)}$$

This is a first idea of chapter 3. From equations (1) and (2) we can obtain $E_r(r,\ t)$. However electric field must be changed to $E_r(R,\ T)$, because $R=kr$ and $T=\omega t$ have the same unit radian as shown in the third line of equation (2). The first line of (2) becomes as follows:

$$E_r(R,\ T)=2A\cos\theta/R^3\ \mathrm{Re}\{(1+jR)\exp j(T-R)\}$$
$$=2A\cos\theta/R^3\ \mathrm{Re}\{(1+jR)(\cos(T-R)+j\sin(T-R)\}$$

$$E_r(R,\ T)=2A\cos\theta/R^3\{\cos(R-T)+R\sin(R-T)\}$$

For electric field $E_\theta(R,\ T)$, in $\{\quad\}$ of equation (1), we use relation of $E_r(R,\ T)-(kr)^2=E_\theta(R,\ T)$. Then next solution can be obtained

$$E_\theta(R,\ T)=A\sin\theta/R^3\{\cos(R-T)+R\sin(R-T)-R^2\cos(R-T)\}$$

From equation (1.1) and (2), the fifth equality sign is obtained in (3). This fifth formula and electric fields $E_r(R,T),\ E_\theta(R,T)$ are used for differential equation. Equation (4) is function 1/*R*. Equation (5) is function $1/u,\ u=R\sin(R-T)+\cos(R-T)$.

Numerator of these function are *dR* for function 1/*R* as shown right side of (4). For function 1/*u* numerator is shown in (5). Right side function of second equality of (4) is 1/*S*, $S=\sin\theta$. Numerator is determined as shown in (4)

From equation (4) we obtain next differential equation.

$$\frac{dR}{R}-\frac{du}{u}=\frac{2\,dS}{S}\quad\because\ S=\sin\theta,\ \ \frac{dS}{d\theta}=\cos\theta,\ \ dS=\cos\theta\cdot d\theta$$

Integral of left and right are as follows, *a* is integration constant

$$\int\left(\frac{dR}{R}-\frac{du}{u}\right)dR=\log a+\log R-\log u,\qquad 2\int\left(\frac{dS}{S}\right)dS=2\log S=\log S^2$$

When both results of integral are equal as follows, dipole shown in Fig,4 radiate electromagnetic waves. Their line of electric forces are determined by next equations

$$\log a+\log R-\log u=\log S^2\quad\therefore\quad aR/u=S^2$$

By substitution of *u* and *S*, final equation becomes as follows,

$$\frac{aR}{R\sin(R-T)+\cos(R-T)}=\sin^2\theta$$

Utility of this equation is expressed in Reference [11]

4. Invention of TE01 mode waveguide using RLSA

TE01 mode waveguide liquid-level indicator is shown in Fig.8, left side is plane figure. Since liquid-level indicator is FM radar, center frequency is 10GHz and bandwidth is 1 GHz. Wide slots are used. Right side of Fig.8 is cross figure of circular waveguide. Radial line is fed by coaxial cable.

Comparing TE_{01} mode with TE_{11} mode, merits of TE_{01} mode are as follows,

1. At that time for liquid-level indicator, diameter of waveguide is 40mm ~ 80mm. Since TE_{11} mode is fundamental mode, diameter of waveguide is about 20mm. We need waveguide to connect two waveguides different diameter
2. F. 11 is radiation pattern of F. 10. For Fig.8, right direction, that is, radiation for waveguide direction is zero. This is important fact because there is no reflection from bottom of a ship. This is main beam direction of TE_{11} mode
3. From 1. and 2. TE_{01} mode is widely used.

Reference [12] H. Sasazawa, Y. Oshima, K. Sakurai, M. Ando, N. Goto, " Slot coupling in a radial line slot antenna for 12-GHz band satellite TV reception," *IEEE Trannsc. A P*, vol. AP-36, pp..1221-1226, Sept. 1988.