LARGE BANDWIDTH DUAL POLARIZED CIRCULAR SLOT ANTENNA.
APPLICATION TO AN ARRAY IN Ku BAND.

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I. INTRODUCTION. A dual polarization is useful when, for instance the target diffraction matrix analysis is to be known. For mobile equipments having antenna gains in the range 20 dBi, printed technology appears to offer a right solution. The large bandwidth elementary radiating source is a circular slot acting at the second resonance. The characteristics of an isolated large bandwidth circular slot directional elementary source partially embedded in a dielectric substrate are deduced from those of an equivalent circular loop with sinusoïdal current distribution when Babinet's principle is applied. The influence of the width of the slot upon the bandwidth is taken into account. Then a reflector is taken into account using the electrical image principle to give a directional radiation. The central metallic disc is fed at two orthogonal points. Coupling between the two feed points is partly due to the presence of higher modes. An application to an array in Ku band is given.

II. THE ISOLATED CIRCULAR LOOP IN AIR MEDIUM. In a first recent paper [1] we deduced the theoretical radiation resistance of an isolated slot ring resonator in air medium from that of an equivalent plane circular loop with constant current distribution. The radiation resistance $(R_r)_R$ for a thin ring is given by the expression :

$$(R_r)_R = \frac{\pi}{2}\sqrt{\mu_o/\varepsilon_o}\,x^4 \sum_{n=0}^{+\infty} \frac{(-1)^n x^{2n}}{(n+2)(n+1)n!\,(n+\frac{3}{2})} \qquad (1)$$

where 2b and 2a are respectively the diameters of the loop and its constant circular cross section. n was an integer, $x = 2\pi b/\lambda_o$, and $a \ll b \ll \lambda_o = (f\sqrt{\mu_o \varepsilon_o})^{-1}$. When the circumference of the loop is less than $0.8\,\lambda_o$ the constant current radiation resistance agrees quite well with that of the sinusoïdal distribution. A first purpose was to express the radiation resistance of a circular loop in air medium, when its thickness parameter, defined by $\Omega_R = 2\log_e(2\pi b/a)$ (2), is taken into account : [2]. The radiation admittance $(Y_r)_R$ is given by [3] :

$$(Y_r)_R = -\frac{j}{\pi}\sqrt{\varepsilon_o/\mu_o}\,\left[\frac{1}{a_o} + 2\sum_{n=1}^{\infty}\frac{1}{a_n}\right] = (G_r)_R + j(B_r)_R \qquad (3) \quad \text{with } a_o = k_o b K_1,$$

$$a_n = \frac{k_o b}{2}(K_{n+1} + K_{n-1}) - \frac{n^2}{k_o b}K_n \quad \text{and} \quad K_o = \frac{1}{\pi}\log_e\frac{8b}{a} - \frac{1}{2}\int_0^{2k_o b}[\Omega_o(x) + j\,J_o(x)]dx$$

$$K_n = \frac{1}{\pi}\left[\mathcal{K}_o(n\tfrac{a}{b})\,\mathcal{I}_o(n\tfrac{a}{b}) + \log_e(4n) + \gamma - 2\sum_{m=0}^{n-1}(2m+1)^{-1}\right] - \frac{1}{2}\int_0^{2k_o b}[\Omega_{2n}(x) + j\,J_{2n}(x)]dx$$

where $\mathcal{K}_o$ and $\mathcal{I}_o$ are the modified Bessel functions of the second and first kinds, J_{2n} is the Bessel function of the first kind, Ω_{2n} is the Lommel-Weber function, γ is the Euler constant and k_o is the free-space wavenumber. n is an integer. We have : $\Omega_{2n}(x) = \frac{1}{\pi}\int_0^{\pi}\sin(x\sin\theta - 2n\theta)d\theta$

$$\mathcal{I}_o(x) = \frac{1}{\pi}\int_0^{\pi}\cosh(z\cos\theta)d\theta. \qquad \mathcal{K}_o(z) = -\frac{1}{\pi}\int_0^{\pi} e^{\pm z\cos\theta}\{\gamma + \log_e(2z\sin^2\theta)\}d\theta$$

$$J_{2n}(x) = \frac{1}{\pi}\int_0^{\pi}\cos[x\sin\theta - 2n\theta]d\theta$$

At the second resonance that is for $k_o b$ near 1 we put :

$$k_o b = x_r \text{ for } B_{res} = 0 \qquad \text{and} \qquad (R_r)_R = 1/Y_{res}.$$

The table I shows the x_r parameter values and the radiation resistance $(R_r)_R$ related to the ring or circular loop operating at the second resonance

Ω_R	20	18	16	14	13	12	11	10
$k_o b = x_r$	1.034	1.039	1.048	1.061	1.071	1.086	1.110	1.162
$(R_r)_R$ (ohms)	138	139	140	142	144	148	154	173
B_o %	6.8	7.7	9.5	11.3	14.0	15.5	19.6	24.0

Table I

The bandwidth B_o expressed in percent for a V.S.W.R. $\leqslant 2$ is given in Table I. The bandwidth B_o increases with the ring thickness that is when Ω_R decreases.

The current distribution along the loop is given by :

[3] $I(\Phi) = I_o + 2 \sum_{n=1}^{\infty} I_n \cos n\Phi$ (4) with $I_n = \frac{-j}{\pi} \frac{V_o}{a_n} \sqrt{\varepsilon_o/\mu_o}$

V_o is the potential which is applied across a gap in the ring at $\Phi = 0$. We deduced from (3) and (4) the ratio $\left|\frac{I_M}{I_m}\right| = \frac{|I(\Phi)|_{Max}}{|I(\Phi_1)|}$, Φ_1 being the angle Φ for which $\frac{|I(\Phi)|}{V_o}$ is minimum. The phase shift $\Delta\Phi$ between $I(\Phi=180°)$ and $I(\phi=0)$ is of main importance. Table II gives these parameters in terms of Ω_R.

Ω_R	20	18	16	14	13	12	11	10
ϕ_1 (degrees)	90	91	91	91	91	92	93	97
$\left\|\frac{I_M}{I_m}\right\|$ (dB)	23.3	22.0	20.7	19.2	18.2	17.1	15.8	14.0
$\Delta\Phi$ (degrees)	181	182	183	184	185.5	188	192	201

Table II

The current distribution in amplitude and phase along the ring shows that there is a transverse main beam. From the table II we can deduce that the purety of polarization becomes better as the parameter Ω_R increases, that is as the ring thickness decreases. The ideal case would be given by :

$$\Delta\phi = 180°, \qquad \phi_1 = 90° \qquad \text{and} \qquad \left|\frac{I_M}{I_m}\right| = +\infty.$$

These results are confirmed, when the radiated electromagnetic far-field, calculated from the following expressions, is taken into account :

$$\vec{E}(\phi,\theta) = E_\phi(\phi,\theta)\hat{\phi} + E_\theta(\phi,\theta)\hat{\theta}$$

with :

$$E_\phi(\phi,\theta) = -\sqrt{\mu_o/\varepsilon_o}\ \psi \cot g\theta \sum_{n=1}^{\infty} j^n n\, I_n \sin(n\phi) . J_n(k_o b \sin\theta)$$

$$E_\phi(\phi,\theta) = \sqrt{\mu_o/\varepsilon_o}\ \frac{k_o b}{2}\ \psi\{I_o J_1(k_o b\sin\theta) + \sum_{n=1}^{\infty} I_n\, j^n \cos(n\phi) \times [J_{n+1}(k_o b\sin\theta) - J_{n-1}(k_o b\sin\theta)]\}$$

ψ is the free space Green function.

In H plane $(\phi = 0,\theta)$ the cross polarization is given by :

$$\tau(\theta) = E_\theta(\phi=0,\theta)/E_\phi(\phi=0,\theta)$$

In E plane ($\phi=\pi/2,\theta$) the cross polarization is given by :

$$\tau(\theta) = E_\phi(\phi=\pi/2,\theta)/E_\theta(\phi=\pi/2,\theta)$$

The table III and IV gives respectively for Ω_R = 20 and 10 the cross polarization in axis : $\tau_o = \tau(\theta=0)$ in dB and the 3dB beamwidth (in degrees) in "E" and "H" planes in terms of frequency around the second resonance. In each case the cross-polarization level runs through a minimum all the more as the frequency is near the resonance and the ring in thinner (Ω_R=20)

x	τ_o (dB)	θ_{3dB} (degrees) E plane	H plane
0.9	-16.8	84	> 180
0.99	-23	82	144
1.028	-26	82	134
1.07	-24	82	122
1.12	-19.5	80	112
1.20	-14.5	78	110

Ω_R = 20

Table III

x	τ_o (dB)	θ_{3dB} (degrees) E plane	H plane
0.93	-14.9	84	> 180
0.95	-15.5	82	> 180
1.03	-17.2	82	142
1.059	-17.3	82	132
1.09	-17.2	82	124
1.12	-16.7	81	118
1.16	-15.8	80	108
1.19	-15	80	104
1.22	-14.1	78	98
1.32	-11.3	77	84

Ω_R = 10 Table IV

III. THE ISOLATED CIRCULAR SLOT IN AIR MEDIUM. The radiation impedance $(Z_r)_S$ of the circular slot can be deduced by applying Babinet's principle as (fig. 1) : $(Z_r)_S = \frac{1}{4}(Y_r)_R \cdot \frac{\mu_o}{\varepsilon_o} \cdot \frac{1}{\varepsilon_e}$ (5) with $\Omega_S = 2\log_e 4\pi(\frac{r_2+r_1}{r_2-r_1})$

This model, deduced by duality, has an identical bandwidth than the ring one's. At the second resonance we obtained from Table I and for ε_e = 1 the results shown in Table V.

Ω_S	20	18	16	14	13	12	11	10
$\frac{\pi(r_1+r_2)}{\lambda_o}$	1.034	1.039	1.048	1.061	1.071	1.086	1.110	1.162
$(R_r)_S$, Ω	257	256	254	250	247	240	231	205
B_o %	6.8	7.7	9.5	11.3	14.0	15.5	19.6	24.0

Table V

Results shown in Tables II, III and IV are valid when ring currents are changed into electric field across the slot. In table VI we deduced a correct agreement between experiments and theory.

Model	Ω_S	experimental $(R_r)_S$ [7]	theory $(R_r)_S$ Table V
r_1 = 77 r_2 = 82	12	235 ± 10	240
r_1 = 77 r_2 = 79,5	13,3	232 ± 10	247

Table VI

IV. THE ISOLATED CIRCULAR SLOT PARTIALLY EMBEDDED IN A DIELECTRIC SHEET. At resonance, that is for $x_r=(k)_r b = (k_o)\sqrt{\varepsilon_e}\, b$, we can write for the radiation resistance [2] :

$$(R_r)_S^{\varepsilon_e} = (R_r)_S \cdot \varepsilon_e \cdot \frac{1 - \frac{1}{5} + \frac{1}{28} - \frac{1}{180} + \frac{1}{1320} \ldots}{1 - \frac{1}{5\varepsilon_e} + \frac{1}{28\varepsilon_e^2} - \frac{1}{180\,\varepsilon_e^3} + \frac{1}{1320\varepsilon_e^4} \ldots} \quad (6)$$

The bandwidth B_o is divided by $\sqrt{\varepsilon_e}$ as an usual result [5]. The equivalent relative permittivity ε_e is deduced from the dielectric thickness d and relative permittivity ε_r knowledge.

In table VII we compare theoretical results given by our method and transmission-line model analysis [6], with some experimental ones.

Model	r_1 (mm)	r_2 (mm)	d (mm)	f_r (GHz)	ε_r	ε_e	$(R_r)_S$ (Ω) from (3) and (6)	$(R_r)_S$ (Ω) theory [6]	$(R_r)_S$ (Ω) experiments [6]
1	4	4.14	0.78	10	2.17	1.38	325	330	307
2	18.45	18.75	0.635	1.5	10.2	2.93	653	606	575
3	30.48	33.02	6.35	0.72	12	4.36	891	860	

Table VII

V. THE CIRCULAR SLOT DIRECTIONAL ANTENNA. We added reflector parallel to the slot at a distance d, and filled with a dielectric substrate. Then the slot input radiation resistance $(R_r)_S^{\varepsilon_e,d}$ can be written as [2] :

$$(R_r)_S^{\varepsilon_e,d} = (R_r)_S^{\varepsilon_e}\left[1+3\,\frac{\cos 2kd}{(2kd)^2} - 3\,\frac{\sin 2kd}{(2kd)^3}\right] \quad (7) \qquad \text{with } k = k_o\sqrt{\varepsilon_e}.$$

We studied a model with the following parameters : $r_1=3.2$mm, $r_2=3.7$mm, $\varepsilon_r=2.17$ and $d = 3.2$mm. As $d >> r_2-r_1$: $\varepsilon_e=(1+\varepsilon_r)/2$. We deduced $\Omega_S = 10.31$ from the table **V** : $B \# B_o/\sqrt{\varepsilon_e} \simeq 19\%$, and with the table V, (6), (7) : $(R_r)_S^{\varepsilon_e,d} = 144\Omega$. The experimental values are 20 % and 125 ohms.

VI. APPLICATION TO AN ARRAY IN Ku BAND. At the second resonance the circular slot diameter D is such that : $0.33 \leqslant \frac{D}{(\lambda_o)r}\sqrt{\varepsilon_e} \leqslant 0.37$. It has independent feed points for each polarization. Coupling between the feed points is partly due to the presence of higher order modes, which were reduced by means of shorting pins as indicated in fig. 2. The coupling was decreased until -20 dB. Constant spacings between circular slots along lines and columns, equal to $0.68\lambda_o$ and $0.80\lambda_o$ are suitable to obtain correct radiation patterns, and to reduce the complexity of both corporate feeds which can be laid on the same triplate. Theoretical results are in good agreement with experiments.

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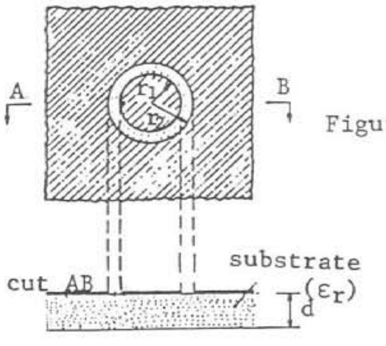

Figure 1

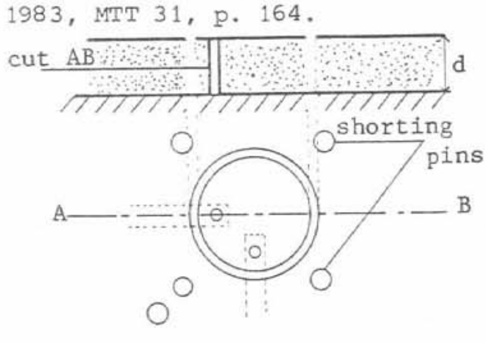

Figure 2