Bird feathers as dielectric rod antennas

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RADIO AND ELECTRICAL ENGINEERING DIVISION

BIRD FEATHERS AS DIELECTRIC ROD ANTENNAS

- E. V. JULL -

OTTAWA

SEPTEMBER 1970

ABSTRACT

Using approximations for the equivalent circuit parameters of a small lossy dielectric post in a waveguide, the dielectric constant and loss tangent of bird feather quills are determined from measurements at 9.3 GHz. From an average relative dielectric constant of about 2.0, it is predicted that a typical chicken quill may be excited as an endfire dielectric rod antenna in the frequency range 30–60 GHz. Results for geese and pigeons are also included.

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BIRD FEATHERS AS DIELECTRIC ROD ANTENNAS

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Introduction

The effect of microwave radiation on birds has been a concern of the Control Systems Laboratory of the Mechanical Engineering Division of NRC and the Neuro-Anatomy Section, of the Anatomy Department of Queen's University. The major objective is to reduce the hazards of birds to aircraft and to this end numerous experiments have been made [1]. They observed that birds respond almost immediately on exposure to 16-GHz field intensities of about 45 mW/cm^2 and take to flight within a few seconds. Lowering the field intensity appears to increase the time taken to initiate flight approximately exponentially [1 (Fig. 3)]. These experiments were made on chickens with 100-watt sources at ranges of about one meter. To achieve the same power density (45 mW/cm^2) at, say, 100 m, with a power source of, for example, 1 kW, would require a paraboloidal reflector with a diameter of at least 2 m and a beamwidth of about $\frac{3}{4}°$. This illustrates the basic difficulty of providing sufficient power to disorient birds quickly in a hazard situation, which has prompted an extensive search for some means of producing similar effects at lower power densities. Such means must almost certainly arise from some non-thermal effect of microwave radiation (see the appendix).

Recently, evidence for non-thermal effects was strengthened by experiments in which only the tail feathers of a chicken were exposed to microwave radiation and agitation of the bird was reported [2]. Plucked chickens were observed to show less susceptibility to microwave exposure, a susceptibility which increased as the feathers grew back. The present investigation was requested by the Control Systems Laboratory on the basis of these results. The dimensions of the feathers are appropriate for their behaviour as dielectric rod antennas at the higher microwave frequencies. It is of interest to know in what frequency range efficient excitation might occur. Consequently measurements were made to determine the microwave behaviour of the feather shaft. If the feather is dry the web portion of it should have little effect on this behaviour.

Microwave Reflectometer Measurements of Quill Sections

Figure 1 shows the dimensions in centimeters of a typical chicken tail feather. The quill or shaft portion of large diameter near the tip is likely to be of major importance in electromagnetic excitation of a dry feather. Since the feather quill is inhomogeneous, the electromagnetic behaviour of an intact quill was desired. Quill sections of 12 feathers cut to the narrow dimension of X-band waveguide, 1.02 cm, were placed across the center of the guide in front of a flat load. With a microwave reflectometer, swept frequency VSWR measurements were made in the range 8.0–10.5GHz. Some of

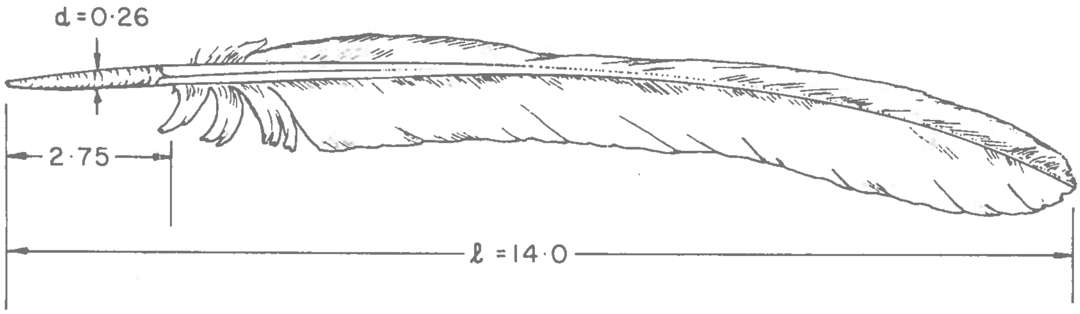

Figure 1 A typical chicken tail feather

these results are shown in Fig. 2. The oscillations in the curves are due to reflections in the experimental arrangement, as was established by inserting an additional length of waveguide. In Fig. 3 the VSWR at 9.3 GHz is seen to be almost proportional to the average diameter of the quill section; i.e., the average of the major and minor axes of

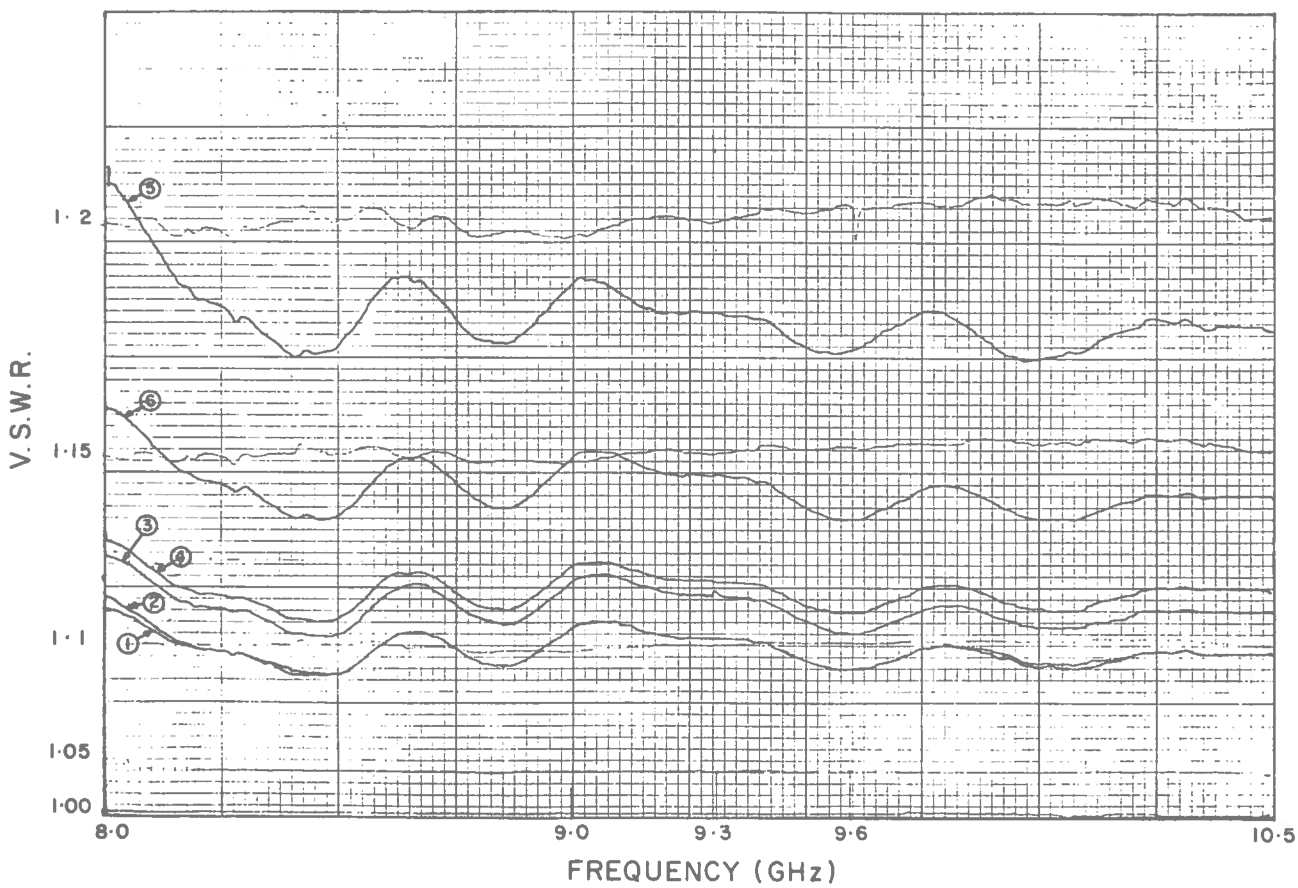

Figure 2 Reflectometer measured VSWR's for 6 quill sections in a waveguide (7/5/70)

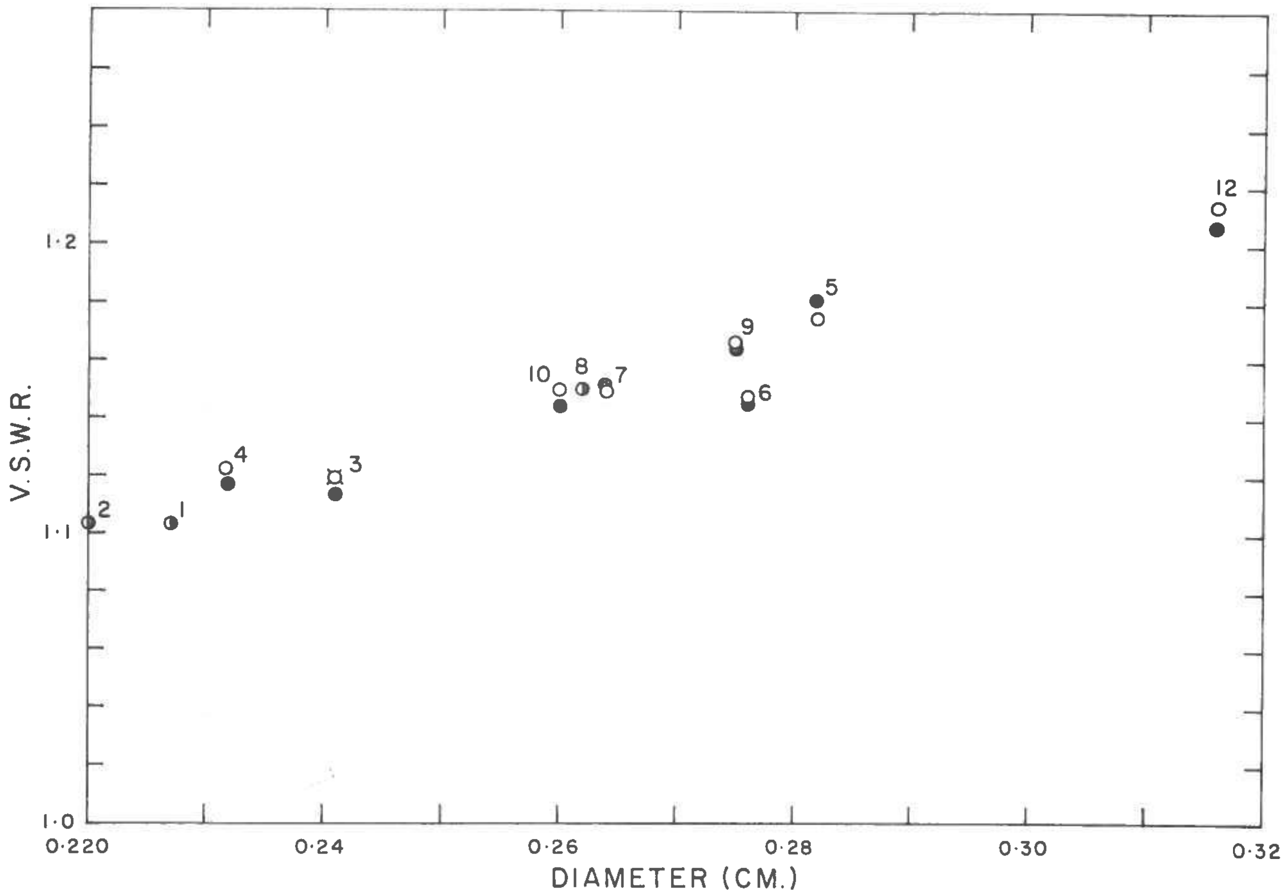

Figure 3 Reflectometer measured VSWR's for quill sections at 9.3 GHz ● 7/5/70 ○ 26/5/70

the almost elliptical quill cross section at the position of maximum shaft size. From these results it may be concluded that the complex dielectric constant of the shaft material does not differ greatly in the various feathers and varies little with frequency in the range 8.0 to 10.5 GHz. The initial set of measurements were made with feathers freshly plucked. Evidently the dielectric constant changed little in a 19-day period at room temperature.

Impedance Measurements of Quill Sections

The complex dielectric constant of the quill specimens cannot be determined from VSWR measurements alone. If the specimen is regarded as a cylindrical dielectric post in a waveguide, the dielectric constant can deduced from its equivalent circuit. From the quill diameters, X-band measurements are most convenient, for at Ku-band the quills are electrically too large to appear as a simple shunt element in a waveguide circuit and at S-band the VSWR will be too small for accurate measurement.

The results of slotted line impedance measurements of the 12 quill specimens are shown in Table 1. The impedance seen is the parallel combination of the quill and the waveguide impedance. The tabulated values Z_a/Z_0 represent the normalized quill impedance alone, which is complex, rather than purely reactive, indicating that the shaft is partially lossy.

The Dielectric Constant of Feather Quills

A cylindrical dielectric post across the center of a waveguide and its equivalent circuit are shown in Fig. 4. If the relative dielectric constant $\epsilon' < 16$, the parameters of the equivalent T-section are, approximately, [3]

$$\frac{X_a}{Z_0} - \frac{X_b}{2Z_0} \approx \frac{a}{2\lambda_g}\left[\frac{2}{(\epsilon'-1)\alpha^2} - S_0 - \frac{1}{4}\frac{\epsilon'-3}{\epsilon'-1}\right], \qquad (1)$$

$$\frac{X_b}{Z_0} \approx \frac{a}{8\lambda_g}\left(\frac{a}{\lambda}\right)^2 (\epsilon'-1)\left(\frac{\pi d}{a}\right)^4\left(1+\frac{\epsilon'-2}{6}\alpha^2\right), \qquad (2)$$

where

$$S_0 = \ln\left(\frac{4a}{\pi d}\right) - 2 + 2\sum_{n=3,5,7,\ldots}^{\infty}\left[\frac{1}{\sqrt{n^2-\left(\frac{2a}{\lambda}\right)^2}} - \frac{1}{n}\right], \qquad (3)$$

$\alpha = \frac{\pi d}{\lambda}$, $\lambda_g = \lambda/\sqrt{1-(\lambda/2a)^2}$ is the guide wavelength and Z_0 is the characteristic impedance of the waveguide. Numerical values of X_a/Z_0 and X_b/Z_0 based on exact expressions have been given for $d/a = 0.05$, 0.10 and 0.15, $\lambda/a = 1.4$ and for values of ϵ' greater than 4 [3]. The above equations, which are accurate to within a few percent for $\epsilon' < 16$, were used to obtain the circuit parameters for values of ϵ' in the range 1–4. These are shown numerically in Table 2 and graphically in Fig. 4. They show that for $\epsilon' < 4.0$ and $d/a < 0.15$, $X_b \ll X_a$ and hence a centered cylindrical dielectric post can be regarded as a simple shunt element with negligible error.

In the 9.3-GHz impedance measurements, $\lambda/a = 3.22/2.29 = 1.41$ and the largest value of d/a for the quill specimens was 0.138. For all specimens the major part of the measured impedance is reactive. If only this is considered, from Fig. 4, the dielectric constant is about 2 and the quills are essentially shunt elements. Hence $X_b = 0$ may be used in (1) yielding

$$\frac{2\lambda_g}{a}\frac{X_a}{Z_0} + S_0 \approx \frac{1}{\epsilon'-1}\left[\frac{2}{\alpha^2} - \frac{\epsilon'-3}{4}\right]. \qquad (4)$$

Further simplification may be made by observing that the largest value of α is 0.31 hence

$$\frac{2}{\alpha^2} \gg \frac{\epsilon'-3}{4}$$

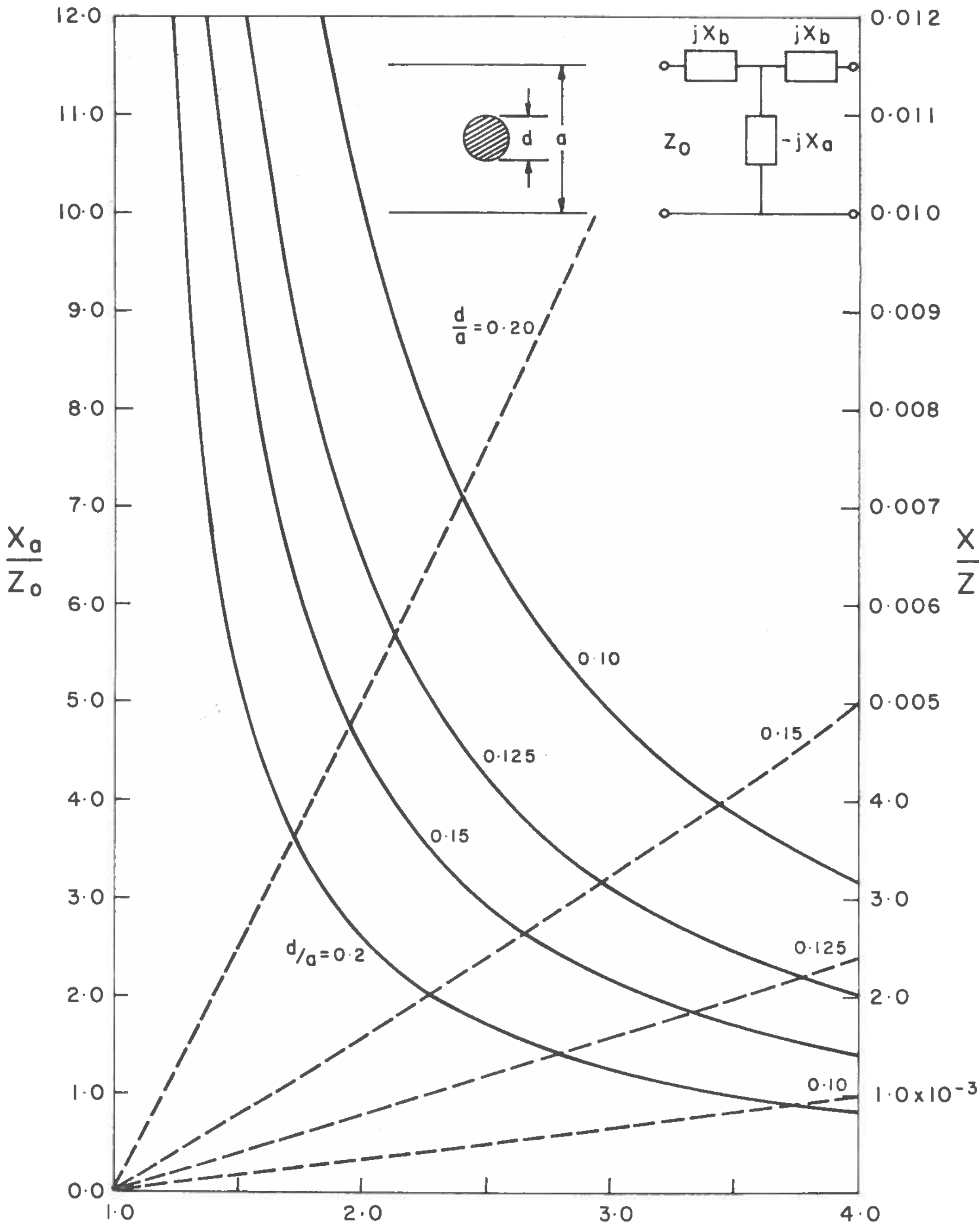

Figure 4 Equivalent circuit parameters of a centered dielectric post in a waveguide —— X_a/Z_0 – – – X_b/Z_0

for all the measurements so that the second term on the right side of (4) is negligible compared to experimental error and

$$\epsilon' \approx 1 + \frac{2}{\alpha^2} \cdot \frac{1}{S_0 + \frac{2\lambda_g}{a} \frac{X_a}{Z_0}} \quad . \tag{5}$$

This expression also applies to a lossy dielectric if ϵ' is replaced by $\epsilon' - j\epsilon''$, where ϵ' and ϵ'' are real and X_a/Z_0 is replaced by $jZ_a/Z_0 = R + jI$ where R and I are real. Making these substitutions in (5) and separating into real and imaginary parts one obtains

$$\epsilon' \approx 1 + \frac{2A}{\alpha^2 D} \quad , \tag{6}$$

and

$$\epsilon'' \approx \frac{2B}{\alpha^2 D} \quad , \tag{7}$$

where

$$A = S_0 + \frac{2\lambda_g}{a} R \ , \tag{8}$$

$$B = \frac{2\lambda_g}{a} I \ , \tag{9}$$

$$D = A^2 + B^2 \tag{10}$$

Using these rather simple expressions the real and imaginary parts of the dielectric constants were obtained from the measured complex reactances for the feather quills. The results are shown in the final columns of Table 1. The dielectric constant is fairly uniform in the specimens, as was indicated by the VSWR measurements, with an average value of $\epsilon' = 1.97$ for the later measured values and a maximum variation from this value of less than 12%. As might be expected, there was more variation in ϵ''; the average value of the loss tangent was $\tan\delta = \epsilon''/\epsilon' = 0.07$.

This procedure is not the most accurate method of obtaining the dielectric constant of materials, but in permitting an intact quill section to be measured natural variations in the structure are included in an effective dielectric constant. The scatter of the measured values suggests uncertainty limits of less than 10% in the average value of ϵ'.

Feather Quills as Dielectric Antennas

For efficient operation as an endfire antenna, a straight cylindrical dielectric rod with an axial taper should have a maximum diameter near its feed point which permits an axial phase velocity of about 0.9 of the free space phase velocity [4, p. 42]. The solution of a transcendental equation for this HE_{11} or dipole mode phase velocity yields a diameter

$$d_{max} = \frac{\lambda}{\sqrt{\pi(\epsilon' - 1)}} \tag{11}$$

for $\epsilon' > 2.3$ [4 (eq. III.10)]. However, it is clear from Fig. 20 of [4] that for $\epsilon' \approx 2$, $d_{max} \approx \lambda/2$ yields approximately the appropriate phase velocity. Since for a straight feather shaft the length $\ell >> d$, this diameter would yield an antenna with rather high sidelobe levels and a $\frac{1}{2}$-field strength total beamwidth of about 35° (Figs. 17 and 16 of [4]). Lower sidelobe levels with about twice this beamwidth are obtained if $d_{max} \approx \lambda/4$.

For the quill specimens examined the average d_{max} was 0.26 cm. The above considerations put the operation of a straight chicken feather shaft as an endfire dielectric rod antenna in the frequency range 30–60 GHz. These frequencies are considerably higher than those presently being used to agitate chickens with essentially broadside illumination of the feathers (16 GHz). Efficient excitation of a chicken feather shaft as a broadside dielectric antenna with the electric field parallel to the shaft (TM_{01} mode) occurs at about 100 GHz, for then the above phase velocity criterion is satisfied with $d_{max} \approx \lambda$ (Fig. 8 of [4]). For a long shaft, the radiation pattern is multilobed with a null along the axis [5]. An isolated wet tail feather shaft, on the other hand, might operate as a monopole antenna at about $\lambda = 4\ell \approx 50$ cm or 0.6 GHz.

Conclusions

It is quite beyond the present knowledge of the writer to describe in engineering terms the receiving circuit attached to the birds' feathers. One might surmise that, since nature did not intend the feathers as electromagnetic receptors, it is inefficient. This investigation only shows that if one had to use a dry chicken feather as a receiving antenna, it should be in the range 30–60 GHz for axial reception and at about 100 GHz for broadside reception. It does not necessarily follow that more efficient agitation of birds by microwaves will occur at higher frequencies for the behaviour of a feather ensemble will be quite different from that of an isolated feather and lossy very new or wet feathers will not behave as dielectric rods at all. It can be said, however, that if feathers are a major factor in agitation of the birds, then more effect is likely to be obtained at these higher frequencies.

Acknowledgments

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Table 1

Measured values of the equivalent circuit, dielectric constant and loss tangent for 12 chicken feather quill specimens 3 weeks after being plucked

	d/a	VSWR	$j\frac{Z_a}{Z_0}$	ϵ'	ϵ''	$\tan\delta$
1	0.098	1.08	$12.67 + j3.53$	1.74	0.20	0.12
2	0.096	1.10	$10.59 + j1.35$	2.00	0.12	0.06
3	0.105	1.12	$8.26 + j1.63$	2.05	0.20	0.10
4	0.102	1.115	$9.17 + j1.75$	2.02	0.19	0.09
5	0.123	1.165	$6.60 + j0.887$	1.98	0.13	0.07
6	0.121	1.140	$7.69 + j0.538$	1.88	0.06	0.03
7	0.115	1.14	$7.26 + j1.32$	2.00	0.18	0.09
		1.165	$6.87 + j0.607$	2.08	0.09	0.04*
8	0.115	1.146	$7.30 + j0.685$	2.03	0.09	0.04
9	0.121	1.158	$6.72 + j0.681$	2.01	0.10	0.05
10	0.114	1.143	$7.28 + j1.32$	2.02	0.18	0.09
11	0.133	1.228	$5.49 + j0.390$	2.02	0.07	0.03
		1.205	$5.94 + j0.846$	1.93	0.13	0.07*
12	0.138	1.198	$5.24 + j1.295$	1.94	0.23	0.12
		1.159	$6.85 + j0.463$	1.76	0.05	0.03*

*3 days after being plucked

Table 2

Calculated values of the approximate equivalent circuit parameters for lossless dielectric posts in a waveguide

$\frac{d}{a}$ =	0.05		0.10		0.125		0.15		0.20	
ϵ	$\frac{X_a}{Z_0}$	$\frac{X_b}{Z_0}$	$\frac{X_a}{Z_0}$	$\frac{X_b}{Z_0}$	$\frac{X_a}{Z_0}$	$\frac{X_b}{Z_0}$	$\frac{X_a}{Z_0}$	$\frac{X_b}{Z_0}$	$\frac{X_a}{Z_0}$	$\frac{X_b}{Z_0}$
1.2	202.8	0.0000	51.05	0.0001	32.88	0.0002	23.02	.0003	13.24	0.0010
1.4	101.2	0.0000	25.41	0.0001	16.35	0.0003	11.44	.0006	6.59	0.0020
1.6	67.34	0.0000	16.86	0.0002	10.84	0.0005	7.59	.0010	4.38	0.0030
1.8	50.40	0.0000	12.59	0.0003	8.09	0.0006	5.66	.0013	3.27	0.0040
2.0	40.24	0.000	10.02	0.0003	6.43	0.0008	4.50	.0016	2.61	0.0050
2.2	33.46	0.000	8.31	0.0004	5.33	0.0009	3.73	.0019	2.16	0.0062
2.4	28.62	0.000	7.09	0.0005	4.55	0.0011	3.18	.0023	1.85	0.0072
2.6	24.99	0.000	6.18	0.0005	3.97	0.0012	2.77	.0026	1.61	0.0082
2.8	22.17	0.000	5.47	0.0006	3.50	0.0014	2.44	.0029	1.43	0.0094
3.0	19.91	0.000	4.90	0.0007	3.13	0.0016	2.19	.0033	1.28	0.0104
3.2	18.07	0.0000	4.43	0.0007	2.83	0.0017	1.98	.0036	1.16	0.0116
3.4	16.53	0.0001	4.04	0.0008	2.58	0.0019	1.80	.0040	1.058	0.0128
3.6	15.22	0.0001	3.71	0.0009	2.37	0.0021	1.65	.0043	0.974	0.0138
3.8	14.11	0.0002	3.43	0.0009	2.19	0.0022	1.53	.0046	0.901	0.0150
4.0	13.14	0.0002	3.19	0.0010	2.03	0.0024	1.42	.0050	0.838	0.0162
	(12.9)	(0.0006)	(3.12)	(0.00093)			(1.39)	(.0049)		

Exact values [3] are bracketed ( ).

Table 3

The dielectric constant and loss tangent of aqueous sodium chloride solutions and steak at 25°C (from ref. [7])

	Frequency (GHz)	0.3	3.0	10.0	25.0
0.0 molal (water)	ϵ'	77.5	76.7	55	34
	tan δ	160	1570	5400	2650
0.1 molal NaCℓ	ϵ'	76	75.5	54	
	tan δ	7800	2400	5600	
0.3 molal NaCℓ	ϵ'	71	69.3	52	
	tan δ	24000	4350	6050	
0.5 molal NaCℓ	ϵ'	69	67.0	51	
	tan δ	39000	6250	6300	
Steak (bottom round)	ϵ'	50	40	30	15
	tan δ	7800	3000	3700	4000

Table 4

Measured values of the equivalent circuit, dielectric constant and loss tangent for freshly plucked goose, pigeon and chicken feather quill specimens

		d/a	VSWR	$j\frac{Z_a}{Z_0}$	ϵ'	ϵ''	$\tan\delta$	Average		
								d(cm)	ϵ'	$\tan\delta$
Goose	1	0.187	1.19	$5.57 + j0.31$	1.52	0.03	0.02			
	2	0.237	1.32	$3.54 + j0.27$	1.51	0.04	0.03			
	3	0.219	1.17	$6.03 + j1.57$	1.33	0.09	0.06	0.503	1.45	0.05
	4	0.238	1.18	$5.71 + j1.86$	1.29	0.09	0.07			
	5	0.219	1.32	$3.33 + j0.67$	1.62	0.13	0.08			
Pigeon	1	0.109	1.09	$10.59 + j1.35$	1.78	0.10	0.05			
	2	0.108	1.10	$10.00 + j2.33$	1.82	0.19	0.10			
	3	0.118	1.06	$17.24 + j5.90$	1.39	0.13	0.09			
								0.257	1.71	0.07
	4	0.114	1.10	$10.98 + j0.22$	1.70	0.01	0.01			
	5	0.115	1.12	$9.28 + j3.12$	1.74	0.25	0.14			
	6	0.112	1.11	$9.62 + j0.92$	1.81	0.08	0.04			
Red Chicken	1	0.143	1.22	$5.03 + j1.07$	1.93	0.19	0.10			
	2	0.136	1.17	$6.03 + j1.59$	1.84	0.22	0.12			
	3	0.140	1.17	$5.96 + j2.21$	1.76	0.28	0.16			
								0.314	1.90	0.12
	4	0.141	1.18	$5.48 + j1.05$	1.90	0.17	0.09			
	5	0.126	1.19	$5.25 + j1.29$	2.12	0.27	0.13			
	6	0.138	1.16	$5.71 + j1.86$	1.83	0.27	0.15			
Black Chicken	1	0.133	1.17	$6.03 + j1.59$	1.87	0.23	0.12			
	2	0.132	1.12	$8.03 + j1.92$	1.68	0.16	0.10			
	3	0.124	1.09	$10.00 + j4.00$	1.57	0.22	0.14			
								0.296	1.75	0.16
	4	0.133	1.15	$7.30 + j0.68$	1.76	0.07	0.40			
	5	0.134	1.14	$7.84 + j0.96$	1.70	0.09	0.05			
	6	0.121	1.15	$6.67 + j2.33$	1.91	0.31	0.16			

Appendix

Some Remarks on the Thermal Effects of Microwave Radiation

In most of the experiments described, pulsed power sources were used [1]. In one set of experiments changing the peak amplitude and pulse width for constant power output appeared to have little effect, while changing the power output did [6 (p. 49)]. There is some indication of more rapid agitation of chickens at 16 GHz as compared to 9.3 GHz [1 (p.126)]. Whether or not this can be attributed simply to increased thermal effects depends on whether the power dissipation

$$\frac{1}{2}\sigma E^2 \quad = \quad \pi f \epsilon' \tan \delta E^2 \ \text{watts/m}^3 \qquad (12)$$

increases appreciably with this frequency change. In (12) $\sigma = 2\pi f \epsilon''$ is the conductivity of the medium, f is the frequency and E is the electric field intensity. Table 3 gives the relative dielectric constant ϵ' and loss tangent $\tan\delta = \epsilon''/\epsilon'$ of sodium chloride solutions at 25°C [7]. The dielectric constant changes little with frequency but large variations in $\tan\delta$ occur in the microwave range. Data are unfortunately not available for chicken flesh. It is, however, possible to make a comparison for beef. For steak, $\tan\delta$ is relatively uniform in the range 3–25 GHz and although ϵ' decreases by a factor of about 0.7 from 9.3 to 16 GHz, the net change in power dissipation is an increase of only about 20% for a uniform field intensity. It is reasonable to suppose that power dissipation also varies little with frequency in chicken flesh.

Measurements on Other Bird Feathers

Impedance and microwave reflection measurements were repeated on quill sections from freshly plucked goose, pigeon, and red and black chicken feathers. The results are shown in Table 4. The larger goose feather quills with lower dielectric constant could behave as endfire dielectric rod antennas in the slightly lower frequency range 25–50 GHz. The other results are little different from those of Table 1.