of the present short paper shows that the agreement between the two methods is, in fact, exact. The ratio of the right-hand side to the left-hand side of (5) was inaccurately given in [7] as 0.981 for the first zero (fundamental Airy mode) and 0.955 for the second zero. We now recognize that this ratio is unity for all the zeros.

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# The Relation of Teratogenesis in *Tenebrio molitor* to the Incidence of Low-Level Microwaves


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***Abstract*—The teratogenic effects of irradiation by low-level microwaves have been studied using the pupae of the darkling beetle *Tenebrio molitor*. For exposures of 2-h duration, statistically significant increases in teratogenesis were observed at waveguide power levels down to 200 $\mu$W; the pupation time increased monotonically with the power. Exposures of various durations and powers at a constant dosage of 4 mW/h strongly suggested that it is the total dosage which determines the level of teratological damage.**


## I. INTRODUCTION

Lindauer *et al.* [1] have reported: 1) that statistically significant teratological damage can be inflicted upon the pupae of the darkling beetle *Tenebrio molitor* by microwave irradiation at 9 GHz and power level of as little as 8.6-mW/cm² CW (10-mW level in WR-90 waveguide) for 2-h exposures; and 2) that there is no significant difference between exposure at 20 mW for 2 h and exposure at 10 mW for 4 h. These observations raised two questions. First, what is the minimum power level which will, with 2-h exposures, have a statistically significant teratogenic effect? Second, since the response of a biological system to a stimulus is often a function of the product of the stimulus intensity and the exposure time, do the results of Lindauer *et al.* [1] indicate the existence of such a reciprocity relation? The experiments described in the following were carried out to answer these questions.


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## II. MATERIAL AND METHODS

One- to two-day-old pupae (nominally, 15-mm length and 5-mm diameter and cultured as reported previously [1]) were mounted for irradiation in Styrofoam blocks and then inserted along the center line of an $X$ band waveguide with their anteriors toward the power source. The experimental arrangement and the microwave circuit for irradiating pupae were the same as those described by Lindauer *et al.* [1], to which the reader is referred for full details and a schematic of the apparatus. The operating frequency was again 9 GHz. The pupae for the control group were mounted in waveguides as if for irradiation but no microwave power was applied. The irradiated pupae and control pupae were placed in individual numbered vials in a darkened environmental chamber at 21°C for the duration of pupation. Using "single blind" techniques, the emergent adults were categorized for gross morphological defects according to the scheme of Carpenter and Livstone [2] where

- $D$ insect died during pupation;
- $G1$ insect developed head and thorax of an adult, but retained the abdomen of a pupa, sometimes with pupal case attached;
- $G2$ adult insect had rumpled and grossly distorted elytra and/or shredded wings;
- $G3$ adult insect was normal except for small discrete holes in elytra;
- $N$ adult insect was apparently normal.

To determine the effects of power level at constant duration of irradiation, pupae were irradiated for 2 h at different levels of incident power, the level being reduced until statistically significant damage was no longer observable with the number of the pupae employed. Pupae absorb roughly $\frac{1}{3}$ of the incident power [1]. The total incident power (in milliwatts) can be converted to power per unit area (in milliwatts per square centimeter) at the center of the WR-90 waveguide employed by multiplying by 0.85; thus, at a level of 20 mW a pupa is exposed to a power density of 17 mW/cm² and is absorbing energy at a rate of roughly $7 \times 10^{-3}$ J/s.

To determine the effects of power level at constant dosage, pupae were given exposures of 4 mW/h (*e.g.*, 2 mW of CW waveguide power for an uninterrupted 2-h exposure) at power levels of $2^{n-1}$ mW ($0 \leq n \leq 5$) and corresponding exposure times of $2^{3-n}$ h.

## III. RESULTS AND STATISTICAL ANALYSIS

The results of irradiation at various power levels are shown in Table I. These data were analyzed by the classic chi-square test [3] with categories $G1$, $G2$, and $G3$ combined to avoid undue emphasis

TABLE I
INCIDENCE OF TERATOGENIC DAMAGE FOR 2 H OF EXPOSURE AT VARIOUS POWER LEVELS

| Group | D | G1 | G2 | G3 | N | Total |
|---|---|---|---|---|---|---|
| 20 mW | 20 (26.7%) | 11 (14.6%) | 23 (30.7%) | 7 (9.3%) | 14 (18.7%) | 75 |
| 10 mW | 21 (26.7%) | 10 (12.5%) | 20 (25.0%) | 5 (6.3%) | 24 (30.0%) | 80 |
| 2 mW | 16 (23.9%) | 6 (9.0%) | 14 (20.9%) | 2 (3.0%) | 29 (43.3%) | 67 |
| 1 mW | 17 (23.3%) | 6 (8.2%) | 15 (20.5%) | 2 (2.7%) | 33 (45.2%) | 73 |
| 0.2 mW | 14 (20.9%) | 5 (7.5%) | 8 (11.9%) | 1 (1.5%) | 39 (58.2%) | 67 |
| 0.1 mW | 21 (20.0%) | 7 (6.7%) | 11 (10.5%) | 1 (1.0%) | 65 (61.9%) | 105 |
| 0.05 mW | 11 (16.2%) | 4 (5.9%) | 6 (8.8%) | 0 (0.0%) | 47 (69.1%) | 68 |
| Control | 54 (18.1%) | 13 (4.4%) | 22 (7.4%) | 1 (0.3%) | 208 (69.8%) | 298 |

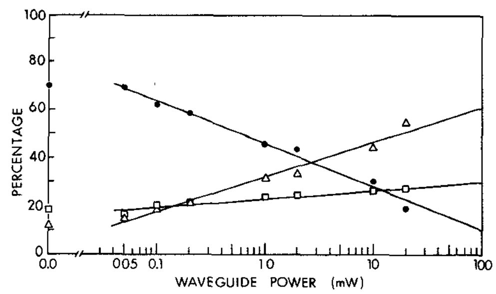


Fig. 1. Percentage of normal (●), damaged (△), and dead (□) adults following 2-h irradiation of day-old pupae at various levels of waveguide power. The percentages were regressed against the logarithms of the power levels (0.05–20 mW) and the following lines determined: normal, $-17.93 \log_{10} P + 45.61$ ($r = -0.99$); damaged, $14.32 \log_{10} P + 31.74$ ($r = 0.99$); dead, $3.60 \log_{10} P - 22.66$ ($r = 0.97$). $P$ is the power in milliwatts and $r$ is the correlation coefficient.

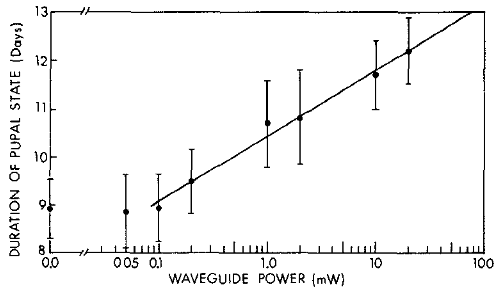


Fig. 2. Duration of pupal state versus waveguide power for the specimens of Table I. The error bars extend for two standard deviations of the sample population. The straight line resulted from regressing duration against the logarithm of the waveguide power (0.1–20 mW); Its equation is $1.37 \log_{10} P + 10.44$ ($r = 0.99$).

on the low rate of occurrence of *G3*. First, various irradiated groups were compared with the control population; all showed differences significant at the 0.05 level except the groups at 0.1 mW and 0.05 mW. Then various groups were compared with one another, there were no significant differences at the 0.05 level between the 2- and 1-mW groups and between the 0.1- and 0.05-mW groups.

These data have been processed and plotted in Fig. 1; it can be seen that the variation in the effect is sensibly linear in the logarithm of waveguide power with an apparent onset of effect in the neighborhood of 0.05 mW. Fig. 2 shows the variation in the duration of the pupal state with waveguide power for these same specimens; it confirms the lengthening noted by Carpenter and Livstone [2] and also displays a logarithmic variation of effect starting roughly at 0.05 mW. This lengthening of pupation period in response to microwave irradiation occurred not only for specimens which developed into adults of all three grades of abnormality but also for specimens which developed into seemingly normal adults.

The results of the test for reciprocity are shown in Table II. The various irradiated groups were again compared with the control group using the chi-square test and all showed significant differences at the 0.05 level. A comparison among different irradiated groups was made by applying a chi-square test for comparing several grouped distributions [3], and there was no significant difference at the 0.05 level.

TABLE II
INCIDENCE OF TERATOGENIC DAMAGE FOR DOSAGE OF 4 mW/h

| Group | D | G1 | G2 | G3 | N | Total |
|---|---|---|---|---|---|---|
| 16 mW, 0.25 hr. | 14 (23.7%) | 6 (10.2%) | 12 (20.3%) | 2 (3.4%) | 25 (42.4%) | 59 |
| 8 mW, 0.5 hr. | 14 (22.6%) | 6 (9.6%) | 13 (21.0%) | 2 (3.2%) | 27 (43.5%) | 62 |
| 4 mW, 1 hr. | 15 (24.6%) | 5 (8.2%) | 13 (21.3%) | 2 (3.3%) | 26 (42.6%) | 61 |
| 2 mW, 2 hr. | 17 (24.2%) | 7 (10.0%) | 14 (20.0%) | 2 (2.9%) | 30 (42.9%) | 70 |
| 1 mW, 4 hr. | 15 (23.8%) | 6 (9.5%) | 13 (20.6%) | 2 (3.2%) | 27 (42.9%) | 63 |
| 0.5 mW, 8 hr. | 15 (22.7%) | 6 (9.1%) | 13 (19.7%) | 2 (3.0%) | 30 (45.4%) | 66 |
| Control | 28 (17.6%) | 7 (4.4%) | 12 (7.5%) | 0 (0.0%) | 112 (70.4%) | 159 |

## IV. DISCUSSION

The results presented in the preceding demonstrate a clear increase in teratological damage due to microwave irradiation and show that it can be statistically significant at total dosages as low as 0.4 mW/h. (0.2 mW applied for 2 h). The data of Table I suggest that the use of larger sample sizes might extend the region of statistically significant damage to somewhat lower dosage levels; the analyses of Figs. 1 and 2 confirm this impression and, additionally, suggest the existence of an apparent onset of effect near 0.1 mW/h, for the sample population studied. Since irradiation at 20 mW is known to produce a measured rise in pupal temperature of less than 2°C [1], and since heating by conventional thermal techniques appear not to be teratogenic [1], [2], one might conclude that the origin of the effects observed here is not thermal in the usual macroscopic sense of this term.

The property of reciprocity demonstrated by the data of Table II is in accord with the observation of Lindauer *et al.* [1] that the results of 20-mW CW for 2 h, 20-mW pulsed (peak power 5 kW) for 2 h, 20-mW pulsed (peak power 50 W) for 2 h, and 10-mW CW for 4 h, are indistinguishable. That is, the available data imply that for sensibly continuous exposures, the teratological damage depends upon the total dose received and not upon protocol by which it is applied. Of course, there are biological phenomena which are reciprocal over some ranges but nonreciprocal over others, or are reciprocal for continuously applied stimuli but become nonreciprocal when the dose is applied intermittently over a sufficiently long period of time.[1] Nevertheless, the available data do at least raise the possibility that microwave photon is a cumulative teratogen.

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# The Coupling of a Single-Ridge Waveguide to a Fabry–Perot Resonator

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***Abstract*—The functional forms of the fields in a single-ridge waveguide are presented. Bethe's small-hole diffraction theory is used to determine the coefficient for coupling from various parts of the guide to a Fabry–Perot (FP) resonator. It is shown that frequency-independent coupling over a very broad band is possible, and specific examples are given for the band from 18.0 to 40.0 GHz.**

## I. INTRODUCTION

In microwave spectroscopy it is often desired to couple single-mode microwave energy from a waveguide into a resonant cavity over a broad band of frequencies. If this band is wider than the bandwidth of a rectangular waveguide, then it is necessary either to use different sizes of rectangular guides over different parts of the band, or to use another type of guide which has a suitable bandwidth. Using more than one type of guide is inadequate if the input energy is to be continuously swept over the band of frequencies. However, a ridge waveguide is very suitable for this application because of its relatively wide single-mode bandwidth. In this paper, an approximate determination of the fields in a single-ridge waveguide and a scheme for broad-band coupling from a single-ridge waveguide into a Fabry–Perot-type (FP) resonant cavity, with particular emphasis on the band of frequencies from 18.0 to 40.0 GHz, are presented.

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## II. DETERMINATION OF BANDWIDTH AND CUTOFF WAVELENGTH

When a rectangular piece of waveguide is loaded with a single ridge down the center (see Fig. 1), the impedance and cutoff frequency are lowered and a wider bandwidth and mode separation are obtained. In order to determine the bandwidth of such a guide, it is necessary to calculate the cutoff wavelengths of the $TE_{m0}$ modes. These wavelengths are usually obtained by assuming parallel-plate TEM modes propagating transversely in the separate rectangular sections of the guide's cross section. The $TE_{m0}$ cutoffs occur at the frequency at which the parallel-plate guide has its $m$th-order resonance. The discontinuity susceptance $B_c$, which occurs at the change in height from one region to the other, must be included in the calculation of these resonances. For $m$-odd modes the resonance must be of the type which gives an infinite impedance at the center of the ridge, while for the $m$-even modes the ridge-center impedance should be zero.

Fig. 2 shows the equivalent circuit for the ridge guide. From this circuit it is seen that for odd resonances the relation that holds is

$$-Y_{01}\cot\left(\frac{2\pi}{\lambda_c}l\right) + B_c + Y_{02}\tan\left(\frac{2\pi}{\lambda_c}\frac{s}{2}\right) = 0 \tag{1}$$

and for even resonances

$$-Y_{01}\cot\left(\frac{2\pi}{\lambda_c}l\right) + B_c - Y_{02}\cot\left(\frac{2\pi}{\lambda_c}\frac{s}{2}\right) = 0. \tag{2}$$

In parallel-plate-type waveguides the characteristic impedance of

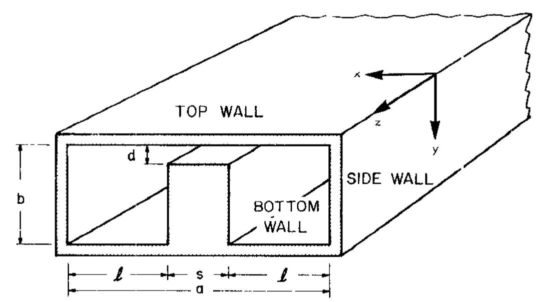


Fig. 1. Configuration of the single-ridge rectangular waveguide showing the coordinate system and the dimensions. $a = 0.712$ cm; $b = 0.3556$ cm; $s = 0.2667$ cm; $d = 0.04953$ cm; $l = 0.2222$ cm.

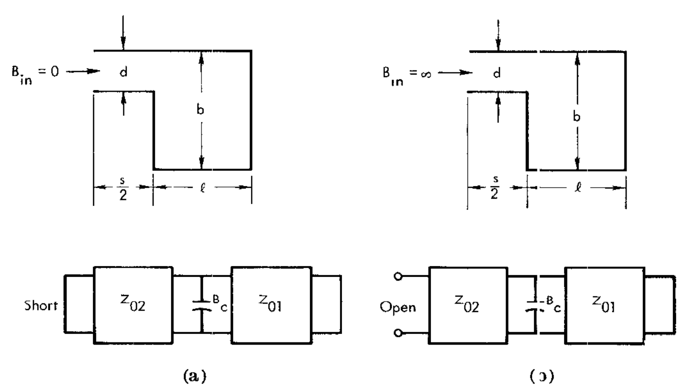


Fig. 2. Equivalent circuits for a single-ridge rectangular waveguide for even and odd modes. (a) For $m$ even. (b) For $m$ odd.