

# Chemical Reactions with a Novel 5.8-GHz Microwave Apparatus. 1. Characterization of Properties of Common Solvents and Application in a Diels–Alder Organic Synthesis

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## Abstract:

Microwave radiation emitted at a frequency of 5.8 GHz in a novel fabricated apparatus is herein proposed for carrying out organic syntheses. Temperature profiles (rates of increase of temperature and superheating) and dielectric parameters are reported for water and 22 common organic solvents. For comparison, solvent properties were also examined using the more common 2.45-GHz microwave radiation under conditions otherwise identical to those used for the 5.8-GHz microwaves. The usefulness of 5.8-GHz microwaves to carry out organic syntheses is demonstrated by the synthesis of 3,6-diphenyl-4-*n*-butylpyridazine through a Diels–Alder process in three representative solvents of various polarities: dichloromethane, ethyl acetate, and xylene. For comparison, the synthesis of 3,6-diphenyl-4-*n*-butylpyridazine was similarly undertaken by conventional heating of the reacting mixture in an oil bath and by 2.45-GHz microwave heating. Results indicate the usage of 5.8-GHz microwaves in organic syntheses might be more beneficial than the 2.45-GHz microwaves.

## 1. Introduction

Studies in microwave-assisted syntheses of organic compounds as a new heating technique have increased since the mid 1980s from reports by Gedye et al.<sup>1</sup> and Giguere and co-workers.<sup>2</sup> Recent years have witnessed extensive use of microwaves in organic syntheses reported in several excellent reviews<sup>3–12</sup> and technical books.<sup>13–15</sup> Several studies noted a decrease of reaction times attributed to the rapid heating induced

by microwave (MW) radiation that was found to be more effective than conventional heating. Other studies examined the microwave effect in, for instance, solvent-free organic reactions<sup>16,17</sup> and rapid organic syntheses induced by microwave radiation under cooled ambient conditions.<sup>18–20</sup> Local heating effects (i.e., hot-spots) in heterogeneous catalyzed reactions have also been investigated.<sup>21,22</sup> Microwave sources used to impart organic reactions generally emitted 2.45-GHz radiation. Reports on the influence of microwave frequencies in microwave-assisted organic syntheses have been rather scarce. For several years the MW frequency response and impact on chemical reactions have been examined in only a few cases. In the field of inorganic chemistry, Möller and Linn<sup>23</sup> used 5.8-GHz microwaves to calcine ceramics and Takizawa and co-workers<sup>24</sup> utilized 28-GHz microwaves for the rapid synthesis of  $(\text{In}_{0.67}\text{Fe}_{0.33})_2\text{O}_3$ , whereas 5.5-GHz microwaves were used<sup>25</sup> in the rapid syntheses of cryptomelane-type manganese oxides for catalysis. In the field of organic chemistry, Gedye and Wei<sup>26</sup> used a variable-frequency microwave oven to effect the Knoevenagel reaction of acetophenone with ethyl cyanoacetate in the presence of piperidine (no solvent; microwave frequency, 8.1 GHz); with anisole as the solvent the reaction was carried out at 12.2 GHz.

The above few reports lend credence to the possibility of 5.8-GHz microwaves becoming an attractive approach as a new heating method in organic chemistry. Advantages of using 5.8-GHz microwaves in organic chemistry are expected and are based on two essential points: (a) the space required for installation of the device can be decreased because the section size of the waveguide is some 3-fold smaller than that of the 2.45-GHz microwaves, and (b) the 5.8-GHz microwaves have a much lower penetration depth. Accordingly, the energy

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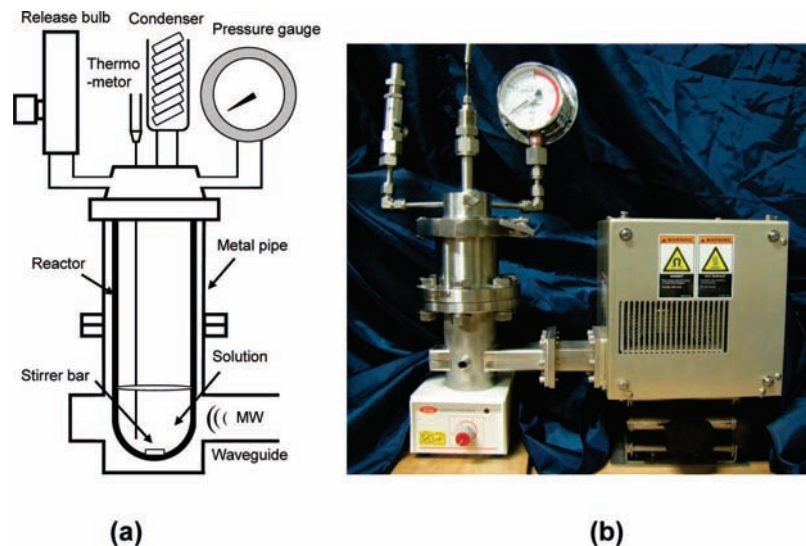
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**Figure 1.** (a) Schematic illustration of the reflux system of the 5.8 GHz microwave system operated in the single mode; (b) photograph of the batch system of the 5.8 GHz microwave chemical reaction system.

efficiency for the heating of thin materials with the 5.8-GHz microwaves is much better than with the 2.45 GHz microwave radiation.<sup>23</sup>

The role of solvents in microwave-assisted organic syntheses is typically based solely on the rate of dissolution of the reacting agents (solvent polarity) and on the magnitude of the solvents' boiling point. Typically, the specific behavior of heating with solvents has been examined using the 2.45-GHz microwave radiation. The principal objectives of the present study were (i) to fabricate a suitable novel device that utilizes 5.8-GHz microwaves; (ii) to compare solvent parameters under microwave radiation for water and several organic solvents typically used in organic syntheses at both 2.45 and 5.8 GHz frequencies; and no less significant (iii) to introduce and explore the merits of 5.8-GHz microwave radiation in organic chemistry by investigating the synthesis of 3,6-diphenyl-4-*n*-butylpyridazine as a model test reaction<sup>27</sup> and examine its dependence on the frequency (5.8 GHz versus 2.45 GHz) of the microwave

radiation. Future studies will examine additional reactions in which the 5.8 GHz microwaves might prove more advantageous.

## 2. Experimental Section

### 2.1. Microwave Apparatus for Chemical Reactions.

The 5.8-GHz frequency microwave generator was a Panasonic M5801 (maximal power 700 W). The high-pressure Pyrex glass cylindrical reactor obtained from Taiatsu Techno Co. {size, 160 mm (H) × 37 mm (i.d.); maximal pressure, 1 MPa; maximal volume, 150 mL} was introduced into the metal pipe connected to the waveguide (see Figure 1). The 5.8-GHz microwaves (single mode) irradiated the reactor through the waveguide {inner size, 40 mm × 20 mm; WRJ-6 (Japan industrial standard); wavelength, 5.17 cm equal to a frequency of 5.8 GHz}. A pressure gauge and a release bulb were connected to the cover of the reactor. The temperature of the reactor solution was monitored using an optical fiber thermometer (FL-2000, Anritsu Meter Co. Ltd.) and a k-type sheathed thermocouple. Variation in reading the temperature from both temperature probes was about ±1 °C. The cylindrical reactor was sealed with a Viton or silicon O-ring and the cover with Teflon. The choice of the O-ring was based on the nature of the solvent used. The system can be used with a reflux condenser (Figure 1a), as a batch system (Figure 1b), or as a flow system using an appropriate pump. Prior to utilization of the apparatus, the position of the reactor relative to the waveguide was tested through a computer simulation using the Comsol Inc. Multi-physics software.

The 2.45-GHz microwave generator (maximal power 200 W) was an ARIOS MP-201 apparatus. The 2.45-GHz microwaves (single mode) irradiated the reactor through the waveguide {inner size, 96 mm × 27 mm; WST-AD (Japan industrial standard); wavelength, 12.24 cm equal to 2.45 GHz}. The incident and reflected power levels of the microwaves were

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measured by the power monitor located before the reactor. The matching of the 2.45-GHz microwave system to the sample was reported earlier.<sup>28</sup>

**2.2. Rates of Temperature Increase and Microwave Properties of Organic Solvents and Water.** A 30-mL sample of various common solvents was introduced into the Pyrex glass cylindrical reactor. The 23 different types of solvents used were: dichloromethane (CH<sub>2</sub>Cl<sub>2</sub>), diethyl ether (C<sub>2</sub>H<sub>5</sub>OC<sub>2</sub>H<sub>5</sub>), ethyl acetate (C<sub>4</sub>H<sub>8</sub>O<sub>2</sub>), acetone (CH<sub>3</sub>COCH<sub>3</sub>), acetic acid (CH<sub>3</sub>-COOH), ethanol (C<sub>2</sub>H<sub>5</sub>OH), methanol (CH<sub>3</sub>OH), 1-propanol (C<sub>3</sub>H<sub>8</sub>O), 2-propanol (C<sub>3</sub>H<sub>8</sub>O), pyridine (C<sub>5</sub>H<sub>5</sub>N), tetrahydrofuran (C<sub>4</sub>H<sub>8</sub>O: THF), dimethylsulfoxide (C<sub>2</sub>H<sub>6</sub>SO: DMSO), 2,5-dimethylfuran (C<sub>6</sub>H<sub>8</sub>O: DMF), triethylamine (C<sub>6</sub>H<sub>15</sub>N), ethylene glycol (C<sub>2</sub>H<sub>4</sub>(OH)<sub>2</sub>), toluene (C<sub>7</sub>H<sub>8</sub>), xylene (C<sub>8</sub>H<sub>10</sub>), cyclohexane (C<sub>6</sub>H<sub>12</sub>), benzene (C<sub>6</sub>H<sub>6</sub>), *n*-hexane (C<sub>6</sub>H<sub>14</sub>), and ion-exchanged water. All organic solvents were used after purification by distillation. The same distilled solvents were used for the experiments with 5.8-GHz and 2.45-GHz microwaves at a power of 30 W by continuous wave irradiation under nonstirred conditions. The increase in temperature caused by the microwave radiation was monitored at 5-s intervals with a fiber-optic thermometer and a thermocouple.

**2.3. Measurements of Dielectric Parameters for Some Common Organic Solvents and Water.** The dielectric constant ( $\epsilon'$ ) and dielectric loss factor ( $\epsilon''$ ) were analyzed with an Agilent Technologies HP-85070B Network analyzer. The dissipation factor ( $\tan \delta$ ) was calculated from these values as  $\tan \delta = \epsilon''/\epsilon'$ . The 5.8- and 2.45-GHz microwave frequencies were interpolated from the frequencies of 5.76 and 5.88 GHz, and 2.34 and 2.46 GHz, respectively. Such measurements can prove difficult to make. In any case, some studies have reported such measurements using a network analyzer using both a perturbation method and a probe method.<sup>29–31</sup> However, it proved difficult to correlate values under these two measurement conditions. Accordingly, in the present work the dielectric parameters of the solvents subjected to 5.8- and 2.45-GHz

microwaves were measured by sequential scans in the same sample, and the measurements were repeated three times using different samples of the same solvent. We found no variations among the measured values.

**2.4. Synthesis of 3,6-Diphenyl-4-*n*-butylpyridazine through a Diels–Alder Process Using 5.8 GHz Microwave Radiation.** An appropriate solution composed of 3,6-diphenyl-1,2,4,5-tetrazine (100 mg, 0.42 mmol) and 1-hexyne (67 mg, 0.84 mmol) in dichloromethane, ethyl acetate, or xylene (10 mL) was heated for 60 and 90 min under 5.8- and 2.45-GHz microwave radiation under stirring conditions. For comparison, the reacting solution was also heated by conventional methods using an oil bath system. The microwave reactor was equipped with a reflux condenser when subjected to 5.8- and 2.45-GHz microwave radiation and when heated by conventional means. The microwave output power of the 5.8- and 2.45-GHz microwaves was kept constant at 30 W. The cylindrical Pyrex reactor, the temperature probes, and the cover were, in all cases, the same components as those used for the 5.8-GHz microwave device. After evaporation of the solvent under reduced pressure, the products were separated and purified by flash column chromatography over Silica gel-300 (ethyl acetate and subsequently by a 50/50 mixture of *n*-hexane and dichloromethane) that yielded the desired product.

The quantity and the purity of the 3,6-diphenyl-4-*n*-butylpyridazine product were ascertained by <sup>1</sup>H NMR spectrometry (JEOL 500 MHz, GX-270 <sup>1</sup>H NMR spectrometer with CDCl<sub>3</sub> as the solvent against TMS as the reference standard) and by mass spectral methods using a JEOL JMS-700 EI-MS mass spectrometer. Identification of the nature of the product used NMR chemical shifts and mass fragmentation patterns as reported by Hoogenboom and co-workers.<sup>27</sup> The resulting data for 3,6-diphenyl-4-butylpyridazine gave, respectively: <sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>)  $\delta$  0.86 (triplet, 3H), 1.30 (sextuplet, 2H), 1.56 (quintuplet, 2H), 2.73 (triplet, 2H), 7.52 (m), 7.70 (singlet, 1H). Mass spectra gave: (EI, 70 eV),  $m/z = 288$  (M<sup>+</sup>, intensity = 63), 259 (M<sup>+</sup> – C<sub>2</sub>H<sub>5</sub>, 100), 245 (M<sup>+</sup> – C<sub>3</sub>H<sub>7</sub>, 13).

### 3. Results and Discussion

**3.1. Rate of Temperature Increase of Organic Solvents and Ion-Exchanged Water.** The rates of temperature increase for some 23 common solvents when subjected to 5.8- and 2.45-GHz microwave radiation are reported in Table 1 (columns 2 and 3). The temperature for each solvent was measured no less than three times without stirring; note that the position of the temperature sensor was shifted by ~3–4 mm for each measurement with an estimated error for each temperature measurement of less than  $\pm 1.5$  °C. Calculation of the rate of increase of temperature in columns 2 and 3 was performed using Excel 2007 from the linear plots ( $y = ax + b$  where  $b$  is the initial temperature and  $a$  is the rate of temperature increase) of temperature against microwave irradiation times at 5 s intervals up to 3 min. In the case of dichloromethane and diethyl ether solvents the data obtained for 1 min of microwave irradiation were employed for the calculations.

The rate of temperature increase with 5.8-GHz microwaves is more than 2-fold faster than for 2.45 Hz for solvents such as *n*-pentane, diethyl ether, dichloromethane, cyclohexane, benzene, triethylamine, hexane, THF, ethyl acetate, and xylene. In

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**Table 1.** Rates of increase of temperature (3 min), ratio of rates, boiling points, time to reach boiling point, and difference between superheating temperature and boiling point for 23 common solvents under nonstirring conditions

1	2		3	4	5	6		7		8		9		10
	rate of increase of temperature in <3 min (deg min <sup>-1</sup> )					ratio of rates (5.8/2.45 GHz)	nature of solvents	boiling point (°C)	time to reach the boiling point (min)		difference between super heating temp. <sup>a</sup> and boiling point °C (minutes to reach super heating temp.)			
solvent	5.8 GHz	2.45 GHz				5.8 GHz	2.45 GHz	5.8 GHz	2.45 GHz	5.8 GHz	2.45 GHz			
<i>n</i> -pentane	2.65	0.10	26.46	nonpolar <sup>c</sup>	36	3.2	>30	11 (10)	– (30)					
diethyl ether	18.09 <sup>b</sup>	1.81 <sup>b</sup>	10.01 <sup>b</sup>	nonpolar	35	0.6	4.2	5 (5)	5 (14)					
dichloromethane	24.16 <sup>b</sup>	3.28 <sup>b</sup>	7.37 <sup>b</sup>	nonpolar	40	0.6	>30	22 (2)	– (30)					
cyclohexane	3.53	0.52	6.80	nonpolar	81	18.5	>30	5 (27)	– (30)					
benzene	3.29	0.54	6.13	nonpolar	80	19.4	>30	8 (28)	– (30)					
triethylamine	11.44	1.92	5.95	nonpolar	90	9.2	>30	8 (9)	– (30)					
hexane	2.66	0.47	5.63	nonpolar	69	26.3	>30	1 (28)	– (30)					
THF	15.80	4.76	3.32	nonpolar	66	2.7	12.5	22 (5)	2 (20)					
ethyl acetate	18.90	7.66	2.47	nonpolar	77	2.9	>30	26 (7.8)	– (30)					
xylene	8.91	4.18	2.13	nonpolar	139	>30	>30	1 (66)	– (66)					
toluene	6.96	4.35	1.60	nonpolar	111	27.3	>30	3 (30)	– (30)					
pyridine	17.21	11.35	1.52	aprotic/polar	115	6.3	>30	7 (7)	– (30)					
acetic acid	16.83	11.26	1.49	protic/polar	101	5.3	8.6	29 (9)	25 (20)					
acetone	16.13	11.57	1.39	aprotic/polar	57	1.8	2.4	22 (5)	15 (5)					
water	8.46	7.15	1.18	protic/polar	100	15.1	15.9	– (30)	2 (17)					
acetic anhydride	14.57	12.60	1.16	aprotic/polar	140	10.0	20.4	18 (15)	2 (25)					
DMSO	14.05	12.45	1.13	aprotic/polar	189	19.8	25.0	13 (27)	2 (30)					
2-propanol	15.77	15.50	1.02	protic/polar	82	4.2	4.0	10 (6)	15 (6)					
DMF	14.82	15.07	0.98	aprotic/polar	153	13.8	20.2	24 (25)	10 (25)					
methanol	13.82	14.83	0.93	protic/polar	65	3.2	2.7	15 (6)	24 (8)					
ethyleneglycol	11.26	12.20	0.92	protic/polar	198	>30	>30	2 (39)	– (39)					
ethanol	15.16	16.45	0.92	protic/polar	78	4.2	3.3	19 (8)	20 (5)					
1-propanol	14.48	16.30	0.89	protic/polar	97	5.3	4.8	20 (10)	20 (10)					

<sup>a</sup> The superheating temperature is given by the boiling point of a solvent in column 6 plus the value given in column 9 or 10. <sup>b</sup> After 1 min of microwave irradiation. <sup>c</sup> The polar or nonpolar nature of the solvents was based on the data reported in McClellan, A. L. Tables of Experimental Dipole Moments; Rahara Enterprises: California, 1989; Vol. 3.

particular, for diethyl ether the rate of microwave-promoted heating was 10-fold faster, whereas for *n*-pentane it was nearly 2.6 orders of magnitude faster when utilizing the 5.8-GHz microwaves relative to the 2.45-GHz radiation. By contrast, for the alcohols such as 1-propanol, ethanol, ethylene glycol, and methanol, together with DMF, the rate of increase was somewhat greater for the 2.45-GHz microwaves. It is noteworthy that for the protic and polar solvents, differences in the rates of heating by a change in the frequency of the microwave radiation (5.8 GHz versus 2.45 GHz) tended to be rather small (see column 4 of Table 1). Even for such a polar molecule as water the rate was 18% faster under 5.8 GHz microwave radiation.

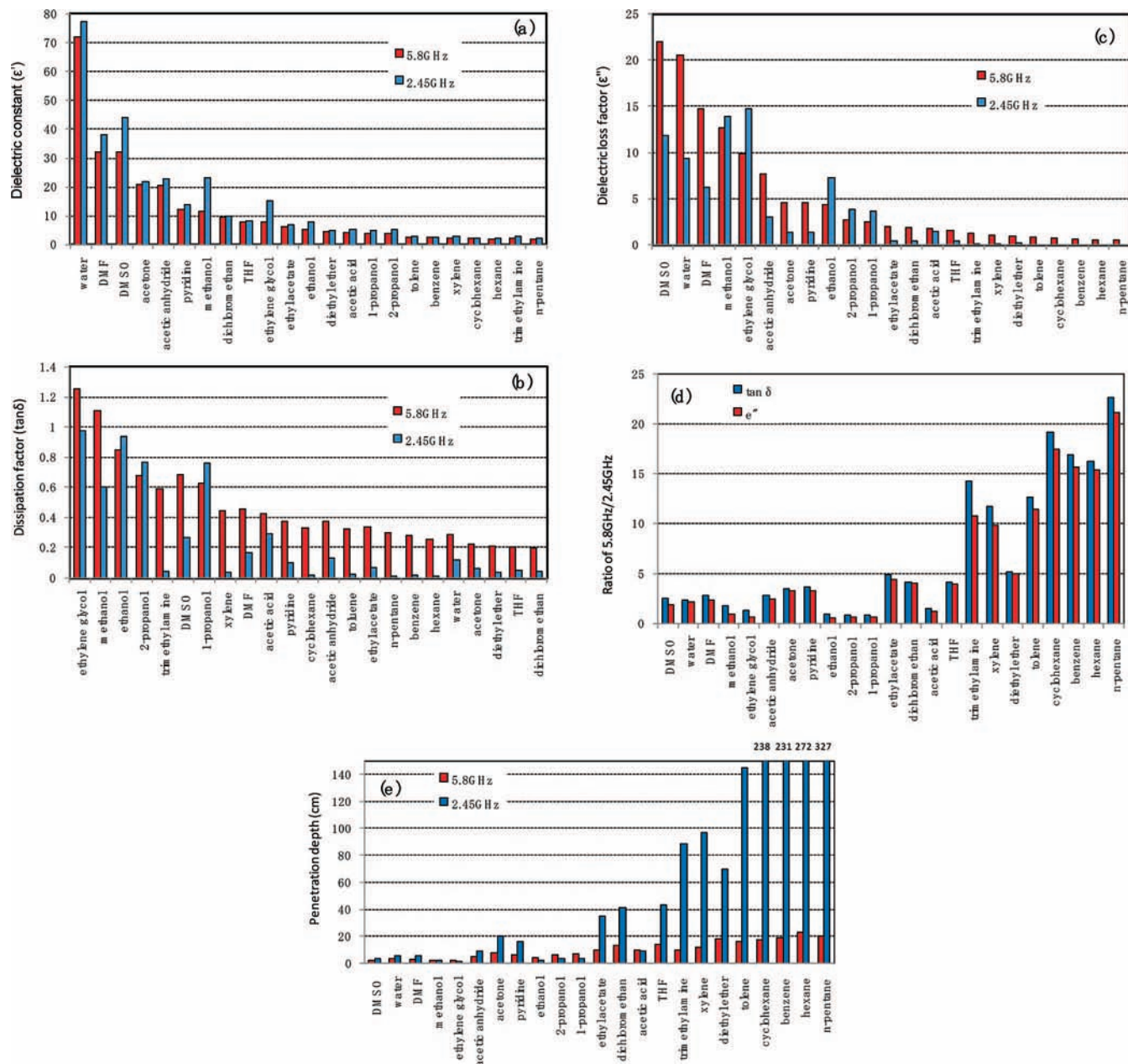
The boiling point of the solvent used is one of several important factors in organic syntheses. In this regard, it is relevant to note that the magnitude of the boiling point achieved by microwave heating is different from that achieved by conventional heating, owing to the superheating effect encountered when microwave radiation is employed. In the case of 5.8-GHz microwave heating, the time to reach the boiling point in less than 3 min was seen for ethyl acetate, THF, acetone, dichloromethane, and diethyl ether (columns 7 and 8). By contrast, heating of ethyl acetate and dichloromethane by the 2.45-GHz microwave radiation required more than 30 min to reach the corresponding boiling points. Superheating was observed for all organic solvents under 5.8 GHz microwave

irradiation (column 9) and for most polar solvents subjected to 2.45-GHz microwaves (column 10). Solvents that displayed a difference greater than 20 °C between the actual temperatures and the boiling points were ethyl acetate, acetic acid, 1-propanol, DMF, THF, acetone, and dichloromethane. Note that the pressure in the cylindrical reactor did not increase as a result of microwave heating because the apparatus was designed as an open system due to the pressure release valve.

The above results indicate that superheating effects were most notable for the 5.8-GHz microwave radiation. Moreover, perusal of the data of Table 1 shows that, when 5.8-GHz microwaves are used, nonpolar solvents present some distinct advantages over the polar solvents in organic syntheses.

### 3.2. Profiles of Solvents under Microwave Irradiation.

The most important characteristics of a solvent under microwave irradiation conditions are the dielectric constant ( $\epsilon'$ ), the dissipation factor ( $\tan \delta$ ), and the dielectric loss factor ( $\epsilon''$ ). The dielectric constant ( $\epsilon'$ ) is a value that depends on the frequency of the microwave radiation and the temperature. The dielectric loss factor ( $\epsilon''$ ) reflects the microwave energy converted to heat.<sup>14</sup> It is a useful index of the generation of heat because of the interaction of the solvent and the microwave radiation field. On the other hand, the ratio  $\epsilon''/\epsilon'$  corresponds to the efficiency by which microwave energy is converted into heat. It is shown as the dissipation factor ( $\tan \delta$ ) which is the dielectric power factor of the dielectric substance. The three main dielectric



**Figure 2.** Dielectric parameters at a microwave frequency of 5.8 and 2.45 GHz for water and 22 pure organic solvents at ambient temperature: (a) dielectric constant,  $\epsilon'$ ; (b) dissipation factor,  $\tan \delta$ ; (c) dielectric loss factor,  $\epsilon''$ ; (d) ratio of dissipation factor ( $\tan \delta$ ) to the dielectric loss factor ( $\epsilon''$ ) at 5.8 and 2.45 GHz microwave frequencies; (e) penetration depth of the microwaves (cm).

parameters are all related to the ability of a solvent to absorb the 2.45-GHz microwave energy.<sup>29–31</sup> The dielectric constants ( $\epsilon'$ ), the dissipation factors ( $\tan \delta$ ), and the dielectric loss factors ( $\epsilon''$ ) of 23 common solvents for the two microwave frequencies of 5.8 and 2.45 GHz at ambient temperature are illustrated in the histograms of Figure 2.

Results show that the dielectric constants ( $\epsilon'$ ) of all the solvents at the 2.45-GHz microwave frequency were greater than the analogous constants at 5.8 GHz (Figure 2a). In particular, the solvents DMSO, methanol, and ethylene glycol displayed significant variations in the dielectric constants. Hence, insofar as dielectric constants are concerned, there are no advantages in using 5.8-GHz microwaves. On the other hand, dissipation factors ( $\tan \delta$ ) for 5.8-GHz microwave radiation are greater than those for 2.45-GHz microwaves for almost all

solvents except ethanol, 2-propanol, and 1-propanol for which  $\tan \delta$ 's are exceptionally greater for the latter microwave frequency (Figure 2b). The higher superheating effect at 5.8 GHz compared to 2.45 GHz microwaves was expected because of the higher dissipation factors at the former microwave frequency over those at 2.45 GHz. This result accords with the notion that the 5.8-GHz microwaves are more efficient in heating the solvents. The dielectric loss factor ( $\epsilon'' = \epsilon'(\tan \delta)$ ), which denotes the product of the dielectric constant ( $\epsilon'$ ) and the dissipation factor ( $\tan \delta$ ), governs the heating efficiency of the solvent when subjected to microwave radiation. The dielectric loss factors ( $\epsilon''$ ) at 5.8 GHz exceeded those at 2.45 GHz for most solvents except the alcohols (Figure 2c). DMSO, water, and DMF displayed the largest  $\epsilon''$  values at 5.8 GHz, whereas at the microwave frequency of 2.45 GHz the dielectric

loss factors for methanol, ethylene glycol, and ethanol were greater than those at 5.8 GHz. Accordingly, the trends of the smaller ratios of the temperature rise for the alcohols and the ethylene glycol at 2.45 GHz (see column 4 of Table 1) were induced by the higher dielectric loss factors at this frequency.

The ratios at 5.8 and 2.45 GHz for the dielectric loss factors ( $\epsilon''$ ) and the dissipation factors ( $\tan \delta$ ) are illustrated in Figure 2d. The higher ratios of the dissipation factors ( $\tan \delta$ ) and dielectric loss factors ( $\epsilon''$ ) of some of the solvents (namely, *n*-pentane, cyclohexane, trimethylamine, benzene, hexane, toluene, and xylene) at 5.8 GHz versus 2.45 GHz are particularly significant. The heating-up rates for these solvents, particularly for the nonpolar solvents, were typically slow under the 2.45-GHz microwave radiation (see column 3 of Table 1). Noteworthy then is the advantage of these  $\epsilon''$  and  $\tan \delta$  parameters at the 5.8 GHz microwave frequency with regard to the effectiveness of microwave-enhanced organic syntheses.

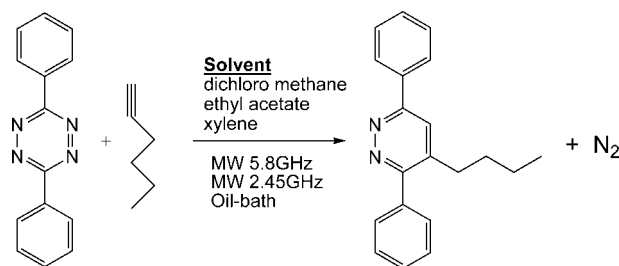
The depth to which the microwave radiation penetrates the microwave-absorbing solvents can be estimated from eq1,<sup>32</sup>

$$d = \frac{1}{2 \left( \sqrt{\frac{1}{2} \omega^2 \epsilon_0 \mu_0 (\sqrt{\epsilon''^2 \epsilon''^2 - \epsilon'^2})} \right)} \quad (1)$$

where  $\epsilon_0$  is the permittivity of free space,  $\mu_0$  is the permeability of free space, and  $\omega$  is the angular frequency. The attenuation ratios of  $\sim 63.2\%$  { $\% = 100 - [100(1 - e)]$ , where  $e$  is the base of the natural logarithms} of the microwave energy for all the solvents are reported in Figure 2e. Penetration of the 5.8-GHz microwaves for all solvents was shallower compared to the depth of penetration by the 2.45-GHz microwaves. For instance, in the case of xylene, the 5.8-GHz microwaves can penetrate to a depth of  $\sim 12$  cm, whereas the depth of penetration is  $\sim 97$  cm for the 2.45-GHz microwaves. In particular, the largest difference in penetration depth between the 5.8-GHz and 2.45-GHz microwaves was observed for the nonpolar solvents. Note that although the 2.45 GHz microwaves penetrate deeper into a solvent/solution, they have a comparatively low energy conversion, whereas the 5.8 GHz microwaves with their shallower penetration depth display a much greater energy conversion.<sup>23</sup> Accordingly, the energy efficiency for heating thin portions of the solvents/solutions is greater when using the 5.8 GHz microwaves. Hence, the penetration depth of the microwaves becomes one of the principal factors that leads to prompt-heating and superheating. As well, the extent of penetration of the microwaves into the solvent medium for many of the solvents examined explains the greater rise ratio of temperature for the nonpolar solvents by the 5.8 GHz microwave radiation (Table 1, column 4).

**3.3. Dominance of the Microwave Frequency.** The microwave-promoted superheating effects seen for the solvents by the 5.8-GHz microwaves are also due, in part, to the relative sizes of the waveguide. The sectional areas of the waveguides for the 5.8-GHz microwaves and the 2.45-GHz microwaves

**Scheme 1**



**Table 2. Chemical yields of 3,6-diphenyl-4-*n*-butylpyridazine under various experimental conditions**

heating method	solvent	reaction temperature (°C)	% yield after	
			60 min	90 min
5.8 GHz (30 W)	dichloromethane	43.5	0	0
	ethyl acetate	81	8	12
	xylene	122	10	12
2.45 GHz (30 W)	dichloromethane	40	0	0
	ethyl acetate	43	0	0
	xylene	33	0	0
oil bath	dichloromethane	40	0	0
	ethyl acetate	76	0	<1
	xylene	135	~2	5

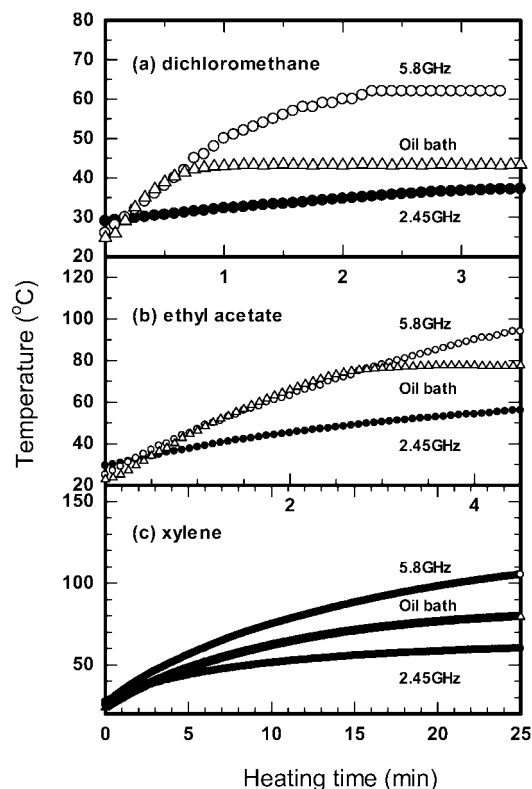
were 40 mm (side)  $\times$  20 mm (height) and 96 mm (side)  $\times$  27 mm (height), respectively. Thus, for the 5.8-GHz microwaves the sectional area was slightly more than 3-fold smaller than for the 2.45-GHz microwaves. Consequently, the power density of the 5.8-GHz microwaves was greater per unit area of the microwave power output. Hence, under the same microwave power of 30 W, the 5.8-GHz microwaves were more efficient in irradiating the solvents than were the 2.45-GHz microwaves.

**3.4. Application of the 5.8-GHz Microwaves in the Synthesis of 3,6-Diphenyl-4-*n*-butylpyridazine.** The overall reaction in forming 3,6-diphenyl-4-*n*-butylpyridazine from the initial diphenyltetrazine and 1-hexyne reagents is indicated in Scheme 1, whereas the chemical yields under various experimental heating conditions after the silica-gel treatment of the resulting product(s) are listed in Table 2.

The yield of the 3,6-diphenyl-4-*n*-butylpyridazine product under 5.8 GHz microwave irradiation was 0% for dichloromethane solvent, 8–12% for ethyl acetate, and a similar yield (10–12%) was obtained when using xylene as the solvent. This was not unexpected for the synthesis of the pyridazine since irradiation of the three solvents used by the 2.45-GHz microwaves was rather comparatively inefficient in temperature increase with time (see below). Irradiation with 2.45-GHz microwaves for longer times also led to no reaction. By contrast, heating the xylene solvent with an oil bath led to a 2–5% yield of 3,6-diphenyl-4-*n*-butylpyridazine; note that the reactor was introduced into the oil bath which had been preheated at 80 °C because the initial rate of temperature rise was rather slow. Although the yields of the pyridazine product under 5.8 GHz microwave radiation are not spectacular, they are nonetheless significantly greater ( $>2\times$ ) than conventional heating of the reacting solution and far better than under 2.45 GHz radiation.

Temperature profiles of the three solvents used (dichloromethane, ethyl acetate and xylene) are illustrated in Figure 3,

(32) Nikawa, Y. Study on safety and protection guideline of electromagnetic waves. *Kokushikan Daigaku Kogakubu Kiyo (Trans. Kokushikan Univ. Dept. Eng.)* 2000., 33, 30–39.



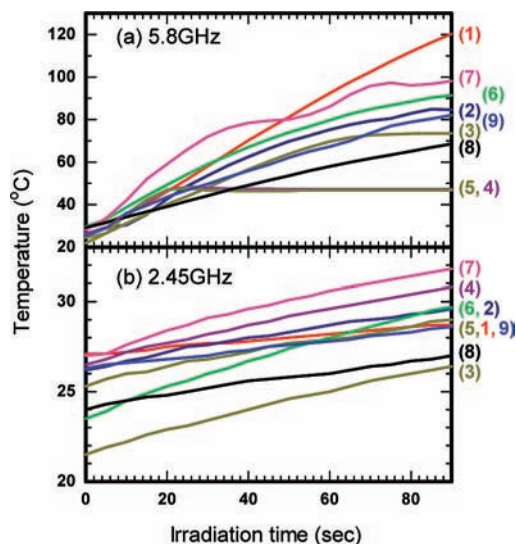
**Figure 3.** Temperature profiles of three solvents, namely (a) dichloromethane, (b) ethyl acetate, and (c) xylene under 5.8 and 2.45 GHz microwave heating, and heating in an oil bath (in all cases the solvents were stirred).

which shows that the 5.8-GHz microwave heating was constantly higher than either for the 2.45-GHz microwaves or the oil bath.

The temperature profiles for the reacting substrates and the solvents used in the open reactor system are shown in Figure 4. The temperature of 3,6-diphenyl-1,2,4,5-tetrazine (tetrazine) and 1-hexyne increased rapidly by the microwave irradiation of 5.8 GHz. Note that the tetrazine is a solid substrate at ambient temperature. The rates of the increase of the temperature of the substrates were greater than those of the solvent used. By contrast, the temperature increases of the solvents were somewhat attenuated for the 2.45-GHz microwaves. The rapid progress of the synthesis of 3,6-diphenyl-4-*n*-butylpyridazine by the 5.8-GHz microwave radiation relative to the 2.45-GHz microwaves must be due to the relatively rapid heating of the nonpolar solvents and of the reacting substrates by the former 5.8-GHz microwaves.

#### 4. Concluding Remarks

Characterization of the novel 5.8-GHz microwave apparatus has been achieved, and its advantages have been recognized on comparing it with 2.45-GHz microwave radiation. Merits of the 5.8-GHz frequency are the prompt heating and superheating by the shallow penetration depth of these microwaves. The novel apparatus thus presents some advantages in microwave-assisted or -enhanced organic syntheses as a result of greater heating efficiencies of nonpolar solvents. Superheating of the



**Figure 4.** Temperature profiles of 3,6-diphenyl-1,2,4,5-tetrazine, 1-hexyne, dichloromethane, ethyl acetate, and xylene using 5.8-GHz and 2.45-GHz microwave heating. {(1) tetrazine, (2) 1-hexyne, (3) tetrazine plus 1-hexyne, (4) dichloromethane, (5) sample in dichloromethane, (6) ethyl acetate, (7) sample in ethyl acetate, (8) xylene, and (9) sample in xylene (note; sample refers to tetrazine plus 1-hexyne)}. In all cases the mixtures were stirred during the temperature measurements.

solvents can be achieved most efficiently by the 5.8-GHz microwave radiation, a feat that the 2.45-GHz microwaves cannot achieve except in a limited number of cases for the alcoholic solvents where the 2.45-GHz microwaves also appear suitable. Moreover, there is no need for a large-scale reactor when using the 5.8-GHz microwave apparatus because of the shallow penetration depth of the microwave radiation. Finally, we have shown that, whereas the organic synthesis of 3,6-diphenyl-4-*n*-butylpyridazine from diphenyltetrazine and 1-hexyne reagents in three chosen solvents occurs, albeit in relatively low yield of ~10–12% in xylene, under 5.8-GHz microwave radiation after a time period of 60–90 min the corresponding yield under conventional heating is even smaller at 2–5%. However, this has to be compared with results under similar conditions but with 2.45-GHz microwaves with which no reaction occurred for the same time period.

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