The 2.45 GHz of a Microwave Oven Is Not a Resonance of Water

— The loss of water at 20 degrees peaks near **17** GHz, and **2.45** GHz sits at only **0.144118** of that, yet it still gets **0.282370** of the peak loss — a resonance with $Q = 10$ at the same place would absorb only **0.001503** — [Paper 571]

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— *From thinking to syncing.* —

Abstract

The 2.45 GHz of a microwave oven is often explained as the resonant frequency of the water molecule.What this paper shows is that in the microwave band the absorption of water is not a resonance but a broad relaxation, that 2.45 GHz lies far from its peak, and that being far is exactly why the food heats inside.No new theorem or law is claimed. First, the absorption of water is a Debye relaxation——with representative values at 20 degrees the relaxation time is 9.3621 ps, the loss peaks at 17 GHz, and 2.45 GHz sits at 0.144118 of it (Section 2). **Second, the loss there is still 0.282370 of the peak——the band is broad: the band absorbing at least half the peak spans exactly $7 + 4\sqrt{3} = 13.928203$ times in frequency, 1.143895 decades** (Section 2). **Third, and this is the core.A resonance with $Q = 10$ at the same place would absorb only 0.001503 of its peak——the relaxation absorbs 187.92 times as much. 2.45 GHz works because water is not resonating** (Section 3). **Fourth, the peak is avoided for the sake of depth——the depth at which the power falls to $1/e$ is 16.4381 mm at 2.45 GHz and 0.5314 mm at 17 GHz, a ratio of 30.9336** (Section 4). **Fifth, at the peak the surface heats 24.5733 times faster——but that is a grill, heating only a thin skin** (Section 4). **Sixth, the separator is whether the molecule has a restoring force——isolated water vapour has rotational resonances; liquid water, in the microwave band, has only friction** (Section 5). **Keywords**: microwave oven, 2.45 GHz, dielectric heating, Debye relaxation, permittivity of water.

Scope of this paper (scope note): **No new theorem or law is claimed——the Debye relaxation and the formulae of dielectric heating are standard.No oven is designed——standing waves in the cavity, uneven heating and the shape of the food are not treated.The numbers are representative——pure water at 20 degrees, with static permittivity 80.2, high-frequency permittivity 5.6 and relaxation frequency 17 GHz.The relaxation is written with one term——water has a smaller, faster relaxation as well, not included.Only the microwave band is discussed——liquid water has intermolecular vibrations in the terahertz and infrared bands; it is not claimed that water has no resonance anywhere.No salt is included——salt dissolved in food adds ionic loss and shortens the penetration depth, outside this paper.The shift with temperature is not computed——the relaxation frequency moves up as water warms, but no numbers are given for it.The penetration depth is taken for normal incidence on a thick flat layer only.The choice of frequency is not credited to physics alone——2.45 GHz is a band allocated to industrial, scientific and medical use; physics says only that the band works.Relation to earlier papers**: **Paper 407 showed that the refractive index for X-rays falls below 1, from the side above the resonances——this paper looks the other way, at an absorption without a resonance, below its peak.Paper 274 stated in its scope note that it would not enter the content of the relaxation-time approximation——the relaxation here is not the scattering of electrons but the lag of molecular orientation; one word, two things.Paper 300 showed that sharing a root is decidable——"absorbed even at 2.45 GHz" and "reaching deep at 2.45 GHz" both come from one root: a broad band and a position far from its peak.**What is added is **finding in the one-term Debye form that the loss at 2.45 GHz is $\mathbf{0.282370}$ of the peak, checked against the closed form, confirming the half-maximum band of $7+4\sqrt{3}$ by bisection and by the closed form, setting against it a resonance at the same place that absorbs only $\mathbf{0.001503}$, obtaining the $\mathbf{30.9336}$ ratio of penetration depths by an exact and an approximate formula**, and **placing the separator on the restoring force**.

1. Notation and the Question

Setting: **the complex permittivity of liquid water is written with one Debye term,**

$$\varepsilon(f)=\varepsilon_\infty+\frac{\varepsilon_s-\varepsilon_\infty}{1+i\,f/f_r}=\varepsilon'-i\varepsilon'',\qquad \varepsilon''=\Delta\varepsilon\,\frac{x}{1+x^2},\quad x=\frac{f}{f_r}$$

with $\Delta\varepsilon=\varepsilon_s-\varepsilon_\infty$.The loss ε'' sets the rate at which the energy of the field turns into heat.

Observation 1.1

microwave ovens are often explained by saying that 2.45 GHz is the resonant frequency of water.A resonance would gather the absorption into a narrow band around that frequency——like tuning a radio, where a small shift loses the station.

Question: in the microwave band, is the absorption of water a resonance?Where in it does 2.45 GHz lie, and why does that place work?

2. The Shape of a Relaxation

Computation 2.1: with representative values for pure water at 20 degrees ($\varepsilon_s = 80.2$, $\varepsilon_\infty = 5.6$, $f_r = 17$ GHz).The relaxation time is $\tau = 1/(2\pi f_r) = \mathbf{9.3621}$ ps, and 2.45 GHz is $x = \mathbf{0.144118}$.

frequency	ε'	ε''
2.45 GHz	**78.6821**	**10.5324**
17 GHz (peak)		**37.3000**

> **Observation 2.2**
>
> the peak loss is exactly $\Delta\varepsilon/2.37.3000$ is half of 74.6 to 10^{-12}——the peak lies at $x = 1$, that is at $f = f_r$.

Computation 2.3: the loss at 2.45 GHz is **0.282370** of the peak.It matches the closed form $2x/(1+x^2)$ to 10^{-12}.

> **Observation 2.4**
>
> the band is broad.The band absorbing at least half the peak runs from $x = \mathbf{0.267949}$ to $\mathbf{3.732051}$——its ends are exactly $2-\sqrt{3}$ and $2+\sqrt{3}$, a ratio of $7+4\sqrt{3} = \mathbf{13.928203}$, or **1.143895** decades. The ends found by bisection match the closed form to 10^{-9}.

> **Observation 2.5**
>
> the width does not depend on the values for water.As long as there is one Debye term, the ratio is the same 13.928203 for any substance and any temperature——the width is set by the shape, not by the numbers.

3. If It Were a Resonance

Computation 3.1: for comparison, a resonance with $Q = 10$ (a Lorentz oscillator) was placed at the same peak and normalized to 1 there (its value at the peak is 1 to 10^{-12}).

	relaxation (water)	resonance ($Q = 10$)
loss at $x = 0.144118$ (relative to peak)	**0.282370**	**0.001503**
ratio of the ends of the half-maximum band	**13.928203**	**1.105401**

> **Observation 3.2**
>
> **this is the core.A resonance would absorb almost nothing at 2.45 GHz (0.001503 of its peak)——the relaxation absorbs 187.92 times as much. A microwave oven works at 2.45 GHz not because water is resonating, but because it is not.**

> **Observation 3.3**
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> **a resonance is narrow.Its half-maximum band spans 1.105401, against the relaxation's 13.928203 ——"resonance" means this narrowness. If it were narrow, almost nothing would happen at a seventh of the peak frequency.**

4. Why Not Heat at the Peak

Computation 4.1: **the depth at which the power falls to $1/e$ was computed exactly from the imaginary part of the complex refractive index $\sqrt{\varepsilon}$.**

frequency	penetration depth
2.45 GHz	**16.4381** mm
17 GHz (peak)	**0.5314** mm
ratio	**30.9336**

> **Observation 4.2**
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> **checked with another formula.The low-loss approximation $\lambda_0\sqrt{\varepsilon'}/(2\pi\varepsilon'')$ gives 16.4015 mm at 2.45 GHz, 0.997778 of the exact value——the two formulae agree to a little over 0.2 per cent.**

Observation 4.3

at the peak the surface is fast.The heat per unit volume goes as $f\varepsilon''$, so 17 GHz heats 24.5733 times faster than 2.45 GHz——but the heat is confined to a skin of 0.5314 mm and can reach the inside only by conduction. That is how a grill heats.

Observation 4.4

being off the peak is the design.2.45 GHz gives up absorption to 0.282370 of the peak and gains 30.9336 times the depth——absorbing strongly and reaching deep cannot be had at one frequency.

5. The Separator

Observation 5.1

the separator is whether the molecule has a restoring force.A resonance has a restoring force and inertia ——a molecule of liquid water is tied to its neighbours by hydrogen bonds, and when the field pulls it round, friction beats any restoring force in the microwave band. The absorption becomes a relaxation, with no narrow peak.

Observation 5.2

the same molecule in the gas does resonate.Isolated water vapour has a narrow rotational line at 22.235 GHz——"the resonance of water" is a property of the isolated molecule, not of liquid water.

Observation 5.3

a counterpart to Paper 407.There the refractive index for X-rays fell below 1 at frequencies above the resonances——the side above the peak of a system that resonates. Here it is the side below the peak of an absorption that does not.

Observation 5.4

not the relaxation of Paper 274.Its scope note declined to enter the content of the relaxation-time approximation——there the relaxation was the scattering of electrons; here it is the lag of molecular orientation. One word names two different delays.

Observation 5.5

one root, under Paper 300.“Absorbed even at 2.45 GHz” and “reaching deep at 2.45 GHz” come from one root, a broad band and a position far from its peak——narrow the band and the first disappears; move to the peak and the second does.

Observation 5.6

what is not said.It is not claimed that physics chose 2.45 GHz——the frequency is a band allocated to industrial, scientific and medical use. Physics says only that the band lies in the broad tail of the relaxation of water and gives both absorption and depth.

6. Roll Call and Closing

1. **relaxation time 9.3621 ps, 2.45 GHz at $x = 0.144118$** (Computation 2.1): **far from the peak.**
2. **still 0.282370 of the peak loss** (Computation 2.3): **matches the closed form.**
3. **half-maximum band $7 + 4\sqrt{3} = 13.928203$** (Observation 2.4): **a width set by shape alone.**
4. **a resonance would give 0.001503** (Computation 3.1): **the core.**
5. **a resonant band of 1.105401** (Observation 3.3): **narrowness is what resonance means.**
6. **penetration 16.4381 mm against 0.5314 mm** (Computation 4.1): **a ratio of 30.9336.**
7. **approximate to exact 0.997778** (Observation 4.2): **two formulae compared.**
8. **at the peak the surface heats 24.5733 times faster** (Observation 4.3): **a grill.**
9. **the separator is the restoring force** (Observation 5.1): **resonance or relaxation.**
10. **water vapour does resonate** (Observation 5.2): **“the resonance of water” belongs to the isolated molecule.**

Closing: **The 2.45 GHz of a microwave oven is often explained as the resonant frequency of the water molecule.Yet in the microwave band the absorption of liquid water is not a resonance but a relaxation——with representative values**

at 20 degrees the relaxation time is 9.3621 ps, the loss peaks at 17 GHz, and 2.45 GHz sits at 0.144118 of it. The loss there is still 0.282370 of the peak, and the band absorbing at least half the peak spans exactly $7+4\sqrt{3}=13.928203$ times, 1.143895 decades, a width that for one Debye term depends on no substance and no temperature.A resonance with $Q=10$ at the same place would absorb only 0.001503 of its peak——the relaxation absorbs 187.92 times as much. A microwave oven works at 2.45 GHz not because water resonates, but because it does not.The peak is avoided for the sake of depth——the power falls to $1/e$ within 16.4381 mm at 2.45 GHz and 0.5314 mm at 17 GHz, a ratio of 30.9336; the approximate formula gives 16.4015 mm, agreeing to a little over 0.2 per cent. At the peak the surface would heat 24.5733 times faster, but only in a thin skin. Absorbing strongly and reaching deep cannot be had at one frequency, and 2.45 GHz lies between them.The separator is whether the molecule has a restoring force——in liquid water friction wins and the absorption relaxes; in isolated vapour the restoring force wins and a narrow line stands at 22.235 GHz. “The resonance of water” belongs to the isolated molecule, not the liquid. Under Paper 300, “absorbed” and “reaching deep” share one root in a broad band seen far from its peak.Placed among the earlier papers——Paper 407 looked above the peak of a system that resonates; this paper looks below the peak of an absorption that does not. The relaxation of Paper 274 is the scattering of electrons; the one here is the lag of molecular orientation, one word for two things.To be honest——no oven was designed. The numbers are representative values for pure water at 20 degrees, with one relaxation term, no ionic conduction from salt and no shift of the relaxation with temperature; the penetration depth was taken for a thick flat layer only. Nor is it claimed that physics chose 2.45 GHz: the frequency is an allocated band, and physics says only that it gives both absorption and depth.

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