

Lecture 22

Quality Factor of Cavities and Mode Orthogonality

22.1 The Quality Factor of a Cavity

22.1.1 General Concepts

The quality factor of a cavity or its Q measures how ideal or lossless a cavity resonator is. An ideal lossless cavity resonator will sustain free oscillations forever, while most resonators sustain free oscillations for a finite time due to losses coming from radiation, or dissipation in the dielectric material filling the cavity, or resistive loss of the metallic part of the cavity. Because of losses, the free oscillation in a cavity has electromagnetic field with time dependence as follows:

$$\mathbf{E} \propto e^{-\alpha t} \cos(\omega t + \phi_1), \quad \mathbf{H} \propto e^{-\alpha t} \cos(\omega t + \phi_2) \quad (22.1.1)$$

The total time-average stored energy, which is proportional to $\frac{1}{4}\epsilon |\mathbf{E}|^2 + \frac{1}{4}\mu |\mathbf{H}|^2$ is of the form

$$\langle W_T \rangle = \langle W_E \rangle + \langle W_H \rangle = W_0 e^{-2\alpha t} \quad (22.1.2)$$

If there is no loss, $\langle W_T \rangle$ will remain constant. However, with loss, the average stored energy will decrease to e^{-1} of its original value at $t = \frac{1}{2\alpha}$. The Q of a cavity is a measure of the number of free oscillations the field would have before the energy stored decreases to e^{-1} of its original value (see Figure 22.1). In a time interval $t = \frac{1}{2\alpha}$, the number of free oscillations in radians is ωt or $\frac{\omega}{2\alpha}$; hence, the Q is defined to be [31]

$$Q = \frac{\omega}{2\alpha} \quad (22.1.3)$$

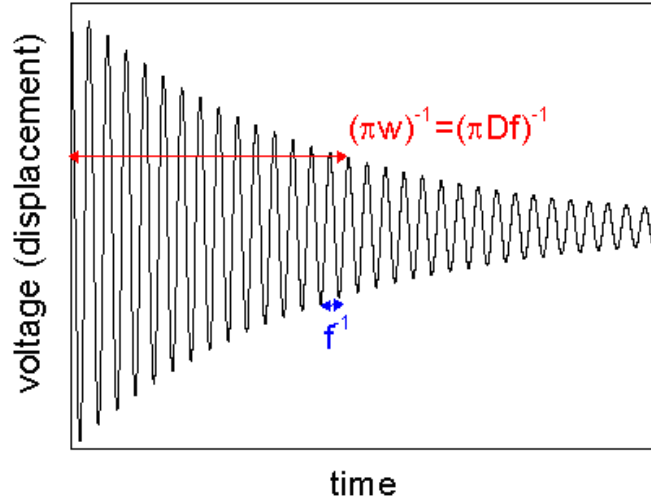


Figure 22.1: A typical time domain response of a high Q system (courtesy of Wikipedia).

Furthermore, by energy conservation, the decrease in stored energy per unit time must be equal to the total power dissipated in the losses of a cavity, in other words,

$$\langle P_D \rangle = -\frac{d\langle W_T \rangle}{dt} \quad (22.1.4)$$

By further assuming that W_T has to be of the form in (22.1.2), then

$$-\frac{d\langle W_T \rangle}{dt} = 2\alpha W_0 e^{-2\alpha t} = 2\alpha \langle W_t \rangle \quad (22.1.5)$$

Hence, we can write equation (22.1.3) as

$$Q = \frac{\omega \langle W_T \rangle}{\langle P_D \rangle} \quad (22.1.6)$$

By further letting $\omega = 2\pi/T$, we lent further physical interpretation to express Q as

$$Q = 2\pi \frac{\langle W_T \rangle}{\langle P_D \rangle T} = 2\pi \frac{\text{total energy stored}}{\text{Energy dissipated/cycle}} \quad (22.1.7)$$

In a cavity, the energy can dissipate in either the dielectric loss or the wall loss of the cavity due to the finiteness of the conductivity.

22.1.2 Relation to the Pole Location

The resonance of a system is related to the pole of the transfer function. For instance, in our previous examples, the reflection coefficient can be thought of as a transfer function in linear

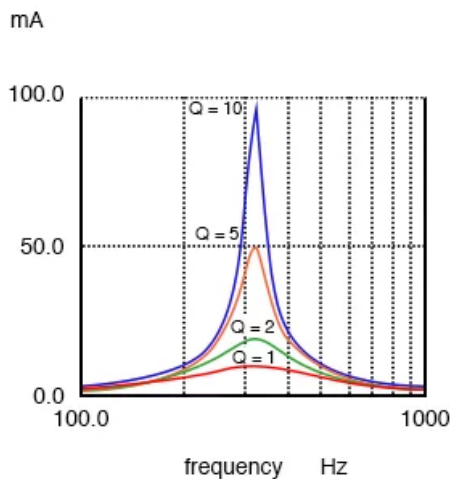
system theory: The input is the incident wave, while the output is the reflected wave. If we encounter the resonance of the system at a particular frequency, the reflection coefficient becomes infinite. This infinite value can be modeled by a pole of the transfer function in the complex ω plane. In other words, in the vicinity of the pole in the frequency domain,

$$R(\omega) \sim \frac{A}{\omega - \omega_p} \quad (22.1.8)$$

In principle, when $\omega = \omega_p$, the reflection coefficient becomes infinite, but this does not happen in practice due to loss in the system. In other words, ω_p is not a real number and the pole does not lie on the real ω axis; the pole is displaced slightly off the real axis to account for loss. In fact, it is quite easy to show that the pole is at $\omega_p = \omega_0 + j\alpha$.¹ Then the full-width half maximum (FWHM) bandwidth is $\Delta\omega = 2\alpha$, and the Q can be written as

$$Q = \omega_0 / \Delta\omega \quad (22.1.9)$$

Typical plots of transfer function versus frequency for a system with different Q 's are shown in Figure 22.2.



A high Q resonant circuit has a narrow bandwidth as compared to a low Q

Figure 22.2: A typical system response versus frequency for different Q 's (courtesy of al-aboutcircuits.com).

¹It is quite easy to show that the Fourier inverse transform of the above corresponds to a decaying sinusoid [45].

22.1.3 Some Formulas for Q for a Metallic Cavity

If the cavity is filled with air, then, the loss comes mainly from the metallic loss or copper-loss from the cavity wall. In this case, the power dissipated on the wall is given by [31]

$$\langle P_D \rangle = \frac{1}{2} \Re \oint_S (\mathbf{E} \times \mathbf{H}^*) \cdot \hat{n} dS = \frac{1}{2} \Re \oint_S (\hat{n} \times \mathbf{E}) \cdot \mathbf{H}^* dS \quad (22.1.10)$$

where S is the surface of the cavity wall.² Here, $(\hat{n} \times \mathbf{E})$ is the tangential component of the electric field which would have been zero if the cavity wall is made of ideal PEC. Also, \hat{n} is taken to be the outward pointing normal at the surface S . However, for metallic walls, $\hat{n} \times \mathbf{E} = \mathbf{H}_t Z_m$ where Z_m is the intrinsic impedance for the metallic conductor, viz., $Z_m = \sqrt{\frac{\mu}{\epsilon_m}} \approx \sqrt{\frac{\mu}{-j\frac{\sigma}{\omega}}} = \sqrt{\frac{\omega\mu}{2\sigma}}(1 + j)$,³ where we have assumed that $\epsilon_m \approx -\frac{j\sigma}{\omega}$, and \mathbf{H}_t is the tangential magnetic field. This relation between \mathbf{E} and \mathbf{H} will ensure that power is flowing into the metallic surface. Hence,

$$\langle P_D \rangle = \frac{1}{2} \Re \oint_S \sqrt{\frac{\omega\mu}{2\sigma}}(1 + j) |\mathbf{H}_t|^2 dS = \frac{1}{2} \sqrt{\frac{\omega\mu}{2\sigma}} \oint_S |\mathbf{H}_t|^2 dS \quad (22.1.11)$$

By further assuming that the stored electric and magnetic energies of a cavity are equal to each other at resonance, the stored energy can be obtained by

$$\langle W_T \rangle = \frac{1}{2} \mu \int_V |\mathbf{H}|^2 dV \quad (22.1.12)$$

Written explicitly, the Q becomes

$$Q = \frac{\sqrt{2\omega\mu\sigma} \int_V |\mathbf{H}|^2 dV}{\oint_S |\mathbf{H}_t|^2 dS} = \frac{2 \int_V |\mathbf{H}|^2 dV}{\delta \oint_S |\mathbf{H}_t|^2 dS} \quad (22.1.13)$$

In the above, δ is the skin depth of the metallic wall. Hence, the more energy stored we can have with respect to the power dissipated, the higher the Q of a resonating system. The lower the metal loss, or the smaller the skin depth, the higher the Q would be.

Notice that in (22.1.13), the numerator is a volume integral and hence, is proportional to volume, while the denominator is a surface integral and is proportional to surface. Thus, the Q , a dimensionless quantity, is roughly proportional to

$$Q \sim \frac{V}{S\delta} \quad (22.1.14)$$

where V is the volume of the cavity, while S is its surface area. From the above, it is noted that a large cavity compared to its skin depth has a larger Q than an small cavity.

²We have used the cyclic identity that $\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \cdot (\mathbf{c} \times \mathbf{a}) = \mathbf{c} \cdot (\mathbf{a} \times \mathbf{b})$ in the above (see Some Useful Mathematical Formulas).

³When an electromagnetic wave enters a conductive region with a large β , it can be shown that the wave is refracted to propagate normally to the surface, and hence, this formula can be applied.

22.1.4 Example: The Q of TM_{110} Mode

For the TM_{110} mode, as can be seen from the previous lecture, the only electric field is $\mathbf{E} = \hat{z}E_z$, where

$$E_z = E_0 \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right) \quad (22.1.15)$$

The magnetic field can be derived from the electric field using Maxwell's equation or Faraday's law, and

$$H_x = \frac{j\omega\epsilon}{\omega^2\mu\epsilon} \frac{\partial}{\partial y} E_z = \frac{j\left(\frac{\pi}{b}\right)}{\omega\mu} E_0 \sin\left(\frac{\pi x}{a}\right) \cos\left(\frac{\pi y}{b}\right) \quad (22.1.16)$$

$$H_y = \frac{-j\omega\epsilon}{\omega^2\mu\epsilon} \frac{\partial}{\partial x} E_z = -\frac{j\left(\frac{\pi}{a}\right)}{\omega\mu} E_0 \cos\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right) \quad (22.1.17)$$

Therefore

$$\begin{aligned} \oint_V |\mathbf{H}|^2 dV &= \int_{-d}^0 \int_0^b \int_0^a dx dy dz \left[|H_x|^2 + |H_y|^2 \right] \\ &= \frac{|E_0|^2}{\omega^2\mu^2} \int_{-d}^0 \int_0^b \int_0^a dx dy dz \\ &\quad \left[\left(\frac{\pi}{b}\right)^2 \sin^2\left(\frac{\pi x}{a}\right) \cos^2\left(\frac{\pi y}{b}\right) + \left(\frac{\pi}{a}\right)^2 \cos^2\left(\frac{\pi x}{a}\right) \sin^2\left(\frac{\pi y}{b}\right) \right] \\ &= \frac{|E_0|^2 \pi^2}{\omega^2\mu^2} \frac{1}{4} \left[\frac{a}{b} + \frac{b}{a} \right] d \end{aligned} \quad (22.1.18)$$

A cavity has six faces, finding the tangential exponent at each face and integrate

$$\begin{aligned} \oint_S |\mathbf{H}_t| dS &= 2 \int_0^b \int_0^a dx dy \left[|H_x|^2 + |H_y|^2 \right] \\ &\quad + 2 \int_{-d}^0 \int_0^a dx dz |H_x(y=0)|^2 + 2 \int_{-d}^0 \int_0^b dy dz |H_y(x=0)|^2 \\ &= \frac{2|E_0|^2}{\omega^2\mu^2} \frac{\pi^2 ab}{4} \left[\frac{1}{a^2} + \frac{1}{b^2} \right] + \frac{2\left(\frac{\pi}{b}\right)^2}{\omega^2\mu^2} |E_0|^2 \frac{ad}{2} + \frac{2\left(\frac{\pi}{a}\right)^2}{\omega^2\mu^2} |E_0|^2 \frac{bd}{2} \\ &= \frac{\pi^2 |E_0|^2}{\omega^2\mu^2} \left[\frac{b}{2a} + \frac{a}{2b} + \frac{ad}{b^2} + \frac{bd}{a^2} \right] \end{aligned} \quad (22.1.19)$$

Hence the Q is

$$Q = \frac{2}{\delta} \frac{\left(\frac{ad}{b} + \frac{bd}{a}\right)}{\left(\frac{b}{2a} + \frac{a}{2b} + \frac{ad}{b^2} + \frac{bd}{a^2}\right)} \quad (22.1.20)$$

The result shows that the larger the cavity, the higher the Q . This is because the Q , as mentioned before, is the ratio of the energy stored in a volume to the energy dissipated over the surface of the cavity.

22.2 Mode Orthogonality and Matrix Eigenvalue Problem

It turns out that the modes of a waveguide or a resonator are orthogonal to each other. This is intimately related to the orthogonality of eigenvectors of a matrix operator.⁴ Thus, it is best to understand this by the homomorphism between the electromagnetic mode problem and the matrix eigenvalue problem. Because of this similarity, electromagnetic modes are also called eigenmodes. Thus it is prudent that we revisit the matrix eigenvalue problem (EVP).

22.2.1 Matrix Eigenvalue Problem (EVP)

It is known in matrix theory that if a matrix is hermitian, then its eigenvalues are all real. Furthermore, their eigenvectors with distinct eigenvalues are orthogonal to each other [69]. Assume that an eigenvalue and an eigenvector exists for the hermitian matrix $\bar{\mathbf{A}}$. Then

$$\bar{\mathbf{A}} \cdot \mathbf{v}_i = \lambda_i \mathbf{v}_i \quad (22.2.1)$$

Dot multiplying the above from the left by \mathbf{v}_i^\dagger where \dagger indicates conjugate transpose, then the above becomes

$$\mathbf{v}_i^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{v}_i = \lambda_i \mathbf{v}_i^\dagger \cdot \mathbf{v}_i \quad (22.2.2)$$

Since $\bar{\mathbf{A}}$ is hermitian, then the quantity $\mathbf{v}_i^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{v}_i$ is purely real. Moreover, the quantity $\mathbf{v}_i^\dagger \cdot \mathbf{v}_i$ is positive real. So in order for the above to be satisfied, λ_i has to be real.

To prove orthogonality of eigenvectors, now, assume that $\bar{\mathbf{A}}$ has two eigenvectors with distinct eigenvalues such that

$$\bar{\mathbf{A}} \cdot \mathbf{v}_i = \lambda_i \mathbf{v}_i \quad (22.2.3)$$

$$\bar{\mathbf{A}} \cdot \mathbf{v}_j = \lambda_j \mathbf{v}_j \quad (22.2.4)$$

Left dot multiply the first equation with \mathbf{v}_j^\dagger and do the same to the second equation with \mathbf{v}_i^\dagger , one gets

$$\mathbf{v}_j^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{v}_i = \lambda_i \mathbf{v}_j^\dagger \cdot \mathbf{v}_i \quad (22.2.5)$$

$$\mathbf{v}_i^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{v}_j = \lambda_j \mathbf{v}_i^\dagger \cdot \mathbf{v}_j \quad (22.2.6)$$

Taking the conjugate transpose of (22.2.5) in the above, and since $\bar{\mathbf{A}}$ is hermitian, their left-hand sides (22.2.5) and (22.2.6) become the same. Subtracting the two equations, we arrive at

$$0 = (\lambda_i - \lambda_j) \mathbf{v}_j^\dagger \cdot \mathbf{v}_i \quad (22.2.7)$$

For distinct eigenvalues, $\lambda_i \neq \lambda_j$, the only way for the above to be satisfied is that

$$\mathbf{v}_j^\dagger \cdot \mathbf{v}_i = C_i \delta_{ij} \quad (22.2.8)$$

Hence, eigenvectors of a hermitian matrix with distinct eigenvalues are orthogonal to each other. The eigenvalues are also real.

⁴This mathematical homomorphism is not discussed in any other electromagnetic textbooks.

22.2.2 Homomorphism with the Waveguide Mode Problem

We shall next show that the problem for finding the waveguide modes or eigenmodes is analogous to the matrix eigenvalue problem. The governing equation for a waveguide mode is BVP involving the reduced wave equation previously derived, or

$$\nabla_s^2 \psi_i(\mathbf{r}_s) + \beta_{is}^2 \psi_i(\mathbf{r}_s) = 0 \quad (22.2.9)$$

with the pertinent homogeneous Dirichlet or Neumann boundary condition, depending on if TE or TM modes are considered. In the above, the differential operator ∇_s^2 is analogous to the matrix operator $\bar{\mathbf{A}}$, the eigenfunction $\psi_i(\mathbf{r}_s)$ is analogous to the eigenvector \mathbf{v}_i , and β_{is}^2 is analogous to the eigenvalue λ_i .

Discussion on Functional Space

To think of a function $\psi(\mathbf{r}_s)$ as a vector, one has to think in the discrete world.⁵ If one needs to display the function $\psi(\mathbf{r}_s)$, on a computer, one will evaluate the function $\psi(\mathbf{r}_s)$ at discrete N locations \mathbf{r}_{ls} , where $l = 1, 2, 3, \dots, N$. For every \mathbf{r}_{ls} or every l , there is a scalar number $\psi(\mathbf{r}_{ls})$. These scalar numbers can be stored in a column vector in a computer indexed by l . The larger N is, the better is the discrete approximation of $\psi(\mathbf{r}_s)$. In theory, one needs N to be infinite to describe this function exactly.⁶

From the above discussion, a function is analogous to a vector and a functional space is analogous to a vector space. However, a functional space is infinite dimensional. But in order to compute on a computer with finite resource, such functions are approximated with vectors. Infinite dimensional vector spaces are replaced with finite dimensional ones to make the problem computable. Such infinite dimensional functional space is also called Hilbert space.

It is also necessary to define the inner product between two vectors in a functional space just as inner product between two vectors in an matrix vector space. The inner product (or dot product) between two vectors in matrix vector space is

$$\mathbf{v}_i^t \cdot \mathbf{v}_j = \sum_{l=1}^N v_{i,l} v_{j,l} \quad (22.2.10)$$

The analogous inner product between two vectors in function space is⁷

$$\langle \psi_i, \psi_j \rangle = \int_S d\mathbf{r}_s \psi_i(\mathbf{r}_s) \psi_j(\mathbf{r}_s) \quad (22.2.11)$$

where S denotes the cross-sectional area of the waveguide over which the integration is performed. The left-hand side is the shorthand notation for inner product in functional space or the infinite dimensional Hilbert space.

⁵Some of these concepts are discussed in [34, 121].

⁶In mathematical parlance, the index for $\psi(\mathbf{r}_s)$ is uncountably infinite or nondenumerable.

⁷In many math books, the conjugation of the first function ψ_i is implied, but here, we follow the electromagnetic convention that the conjugation of ψ_i is not implied unless explicitly stated.

Another requirement for a vector in a functional Hilbert space is that it contains finite energy or that

$$\mathcal{E}_f = \int_S d\mathbf{r}_s |\psi_i(\mathbf{r}_s)|^2 \quad (22.2.12)$$

is finite. The above is analogous to that for a matrix vector \mathbf{v} as

$$\mathcal{E}_m = \sum_{l=1}^N |v_l|^2 \quad (22.2.13)$$

The square root of the above is often used to denote the “length” or the “metric” of the vector. Finite energy also implies that the vectors are of finite length. This length is also called the “norm” of a vector.

22.2.3 Proof of Orthogonality of Waveguide Modes

Because of the aforementioned discussion, we see the similarity between a function Hilbert space, and the matrix vector space. In order to use the result of the matrix EVP, one key step is to prove that the operator ∇_s^2 is hermitian. In matrix algebra, a matrix operator is hermitian if

$$\mathbf{x}_i^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{x}_j = \left(\mathbf{x}_j^\dagger \cdot \bar{\mathbf{A}}^\dagger \cdot \mathbf{x}_i \right)^\dagger = \left(\mathbf{x}_j^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{x}_i \right)^\dagger = \left(\mathbf{x}_j^\dagger \cdot \bar{\mathbf{A}} \cdot \mathbf{x}_i \right)^* \quad (22.2.14)$$

The first equality follows from standard matrix algebra,⁸ the second equality follows if $\bar{\mathbf{A}} = \bar{\mathbf{A}}^\dagger$, or that $\bar{\mathbf{A}}$ is hermitian. The last equality follows because the quantity in the parenthesis is a scalar, and hence, its conjugate transpose is just its conjugate.

By the same token, a functional operator ∇_s^2 is hermitian if

$$\langle \psi_i^*, \nabla_s^2 \psi_j \rangle = \int_S d\mathbf{r}_s \psi_i^*(\mathbf{r}_s) \nabla_s^2 \psi_j(\mathbf{r}_s) = (\langle \psi_j^*, \nabla_s^2 \psi_i \rangle)^* = \int_S d\mathbf{r}_s \psi_j(\mathbf{r}_s) \nabla_s^2 \psi_i^*(\mathbf{r}_s) \quad (22.2.15)$$

Using integration by parts for higher dimensions and with the appropriate boundary condition for the function $\psi(\mathbf{r}_s)$, the above equality can be proved.

To this end, one uses the identity that

$$\nabla_s \cdot [\psi_i^*(\mathbf{r}_s) \nabla_s \psi_j(\mathbf{r}_s)] = \psi_i^*(\mathbf{r}_s) \nabla_s^2 \psi_j(\mathbf{r}_s) + \nabla_s \psi_i^*(\mathbf{r}_s) \cdot \nabla_s \psi_j(\mathbf{r}_s) \quad (22.2.16)$$

Integrating the above over the cross sectional area S , and invoking Gauss divergence theorem in 2D, one gets that

$$\begin{aligned} \int_C dl \hat{n} \cdot (\psi_i^*(\mathbf{r}_s) \nabla_s \psi_j(\mathbf{r}_s)) &= \int_S d\mathbf{r}_s (\psi_i^*(\mathbf{r}_s) \nabla_s^2 \psi_j(\mathbf{r}_s)) \\ &+ \int_S d\mathbf{r}_s (\nabla_s \psi_i^*(\mathbf{r}_s) \cdot \nabla_s \psi_j(\mathbf{r}_s)) \end{aligned} \quad (22.2.17)$$

⁸ $(\bar{\mathbf{A}} \cdot \bar{\mathbf{B}} \cdot \bar{\mathbf{C}})^\dagger = \bar{\mathbf{C}}^\dagger \cdot \bar{\mathbf{B}}^\dagger \cdot \bar{\mathbf{A}}^\dagger$ [69].

where C the the contour bounding S or the waveguide wall. By applying the boundary condition that $\psi_i(\mathbf{r}_s) = 0$ or that $\hat{n} \cdot \nabla_s \psi_j(\mathbf{r}_s) = 0$, or a mixture thereof, then the left-hand side of the above is zero. This will be the case be it TE or TM modes.

$$0 = \int_S d\mathbf{r}_s (\psi_i^*(\mathbf{r}_s) \nabla_s^2 \psi_j(\mathbf{r}_s)) + \int_S d\mathbf{r}_s (\nabla \psi_i^*(\mathbf{r}_s) \cdot \nabla_s \psi_j(\mathbf{r}_s)) \quad (22.2.18)$$

Applying the same treatment to the last term (22.2.15), we get

$$0 = \int_S d\mathbf{r}_s (\psi_j(\mathbf{r}_s) \nabla_s^2 \psi_i^*(\mathbf{r}_s)) + \int_S d\mathbf{r}_s (\nabla \psi_i^*(\mathbf{r}_s) \cdot \nabla_s \psi_j(\mathbf{r}_s)) \quad (22.2.19)$$

The above indicates that

$$\langle \psi_i^*, \nabla_s^2 \psi_j \rangle = (\langle \psi_j^*, \nabla_s^2 \psi_i \rangle)^* \quad (22.2.20)$$

proving that the operator ∇_s^2 is hermitian. One can then use the above property to prove the orthogonality of the eigenmodes when they have distinct eigenvalues, the same way we have proved the orthogonality of eigenvectors. The above proof can be extended to the case of a resonant cavity. The orthogonality of resonant cavity modes is analogous to the orthogonality of eigenvectors of a hermitian operator.

Bibliography

- [1] J. A. Kong, *Theory of electromagnetic waves*. New York, Wiley-Interscience, 1975.
- [2] A. Einstein *et al.*, “On the electrodynamics of moving bodies,” *Annalen der Physik*, vol. 17, no. 891, p. 50, 1905.
- [3] P. A. M. Dirac, “The quantum theory of the emission and absorption of radiation,” *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, vol. 114, no. 767, pp. 243–265, 1927.
- [4] R. J. Glauber, “Coherent and incoherent states of the radiation field,” *Physical Review*, vol. 131, no. 6, p. 2766, 1963.
- [5] C.-N. Yang and R. L. Mills, “Conservation of isotopic spin and isotopic gauge invariance,” *Physical review*, vol. 96, no. 1, p. 191, 1954.
- [6] G. t’Hooft, *50 years of Yang-Mills theory*. World Scientific, 2005.
- [7] C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation*. Princeton University Press, 2017.
- [8] F. Teixeira and W. C. Chew, “Differential forms, metrics, and the reflectionless absorption of electromagnetic waves,” *Journal of Electromagnetic Waves and Applications*, vol. 13, no. 5, pp. 665–686, 1999.
- [9] W. C. Chew, E. Michielssen, J.-M. Jin, and J. Song, *Fast and efficient algorithms in computational electromagnetics*. Artech House, Inc., 2001.
- [10] A. Volta, “On the electricity excited by the mere contact of conducting substances of different kinds. in a letter from Mr. Alexander Volta, FRS Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir Joseph Banks, Bart. KBPR S,” *Philosophical transactions of the Royal Society of London*, no. 90, pp. 403–431, 1800.
- [11] A.-M. Ampère, *Exposé méthodique des phénomènes électro-dynamiques, et des lois de ces phénomènes*. Bachelier, 1823.
- [12] —, *Mémoire sur la théorie mathématique des phénomènes électro-dynamiques uniquement déduite de l’expérience: dans lequel se trouvent réunis les Mémoires que M. Ampère a communiqués à l’Académie royale des Sciences, dans les séances des 4 et*

26 décembre 1820, 10 juin 1822, 22 décembre 1823, 12 septembre et 21 novembre 1825. Bachelier, 1825.

- [13] B. Jones and M. Faraday, *The life and letters of Faraday*. Cambridge University Press, 2010, vol. 2.
- [14] G. Kirchhoff, “Ueber die auflösung der gleichungen, auf welche man bei der untersuchung der linearen vertheilung galvanischer ströme geführt wird,” *Annalen der Physik*, vol. 148, no. 12, pp. 497–508, 1847.
- [15] L. Weinberg, “Kirchhoff’s’ third and fourth laws’,” *IRE Transactions on Circuit Theory*, vol. 5, no. 1, pp. 8–30, 1958.
- [16] T. Standage, *The Victorian Internet: The remarkable story of the telegraph and the nineteenth century’s online pioneers*. Phoenix, 1998.
- [17] J. C. Maxwell, “A dynamical theory of the electromagnetic field,” *Philosophical transactions of the Royal Society of London*, no. 155, pp. 459–512, 1865.
- [18] H. Hertz, “On the finite velocity of propagation of electromagnetic actions,” *Electric Waves*, vol. 110, 1888.
- [19] M. Romer and I. B. Cohen, “Roemer and the first determination of the velocity of light (1676),” *Isis*, vol. 31, no. 2, pp. 327–379, 1940.
- [20] A. Arons and M. Peppard, “Einstein’s proposal of the photon concept—a translation of the Annalen der Physik paper of 1905,” *American Journal of Physics*, vol. 33, no. 5, pp. 367–374, 1965.
- [21] A. Pais, “Einstein and the quantum theory,” *Reviews of Modern Physics*, vol. 51, no. 4, p. 863, 1979.
- [22] M. Planck, “On the law of distribution of energy in the normal spectrum,” *Annalen der physik*, vol. 4, no. 553, p. 1, 1901.
- [23] Z. Peng, S. De Graaf, J. Tsai, and O. Astafiev, “Tuneable on-demand single-photon source in the microwave range,” *Nature communications*, vol. 7, p. 12588, 2016.
- [24] B. D. Gates, Q. Xu, M. Stewart, D. Ryan, C. G. Willson, and G. M. Whitesides, “New approaches to nanofabrication: molding, printing, and other techniques,” *Chemical reviews*, vol. 105, no. 4, pp. 1171–1196, 2005.
- [25] J. S. Bell, “The debate on the significance of his contributions to the foundations of quantum mechanics, Bells Theorem and the Foundations of Modern Physics (A. van der Merwe, F. Selleri, and G. Tarozzi, eds.),” 1992.
- [26] D. J. Griffiths and D. F. Schroeter, *Introduction to quantum mechanics*. Cambridge University Press, 2018.
- [27] C. Pickover, *Archimedes to Hawking: Laws of science and the great minds behind them*. Oxford University Press, 2008.

- [28] R. Resnick, J. Walker, and D. Halliday, *Fundamentals of physics*. John Wiley, 1988.
- [29] S. Ramo, J. R. Whinnery, and T. Duzer van, *Fields and waves in communication electronics, Third Edition*. John Wiley & Sons, Inc., 1995.
- [30] J. L. De Lagrange, “Recherches d’arithmétique,” *Nouveaux Mémoires de l’Académie de Berlin*, 1773.
- [31] J. A. Kong, *Electromagnetic Wave Theory*. EMW Publishing, 2008.
- [32] H. M. Schey, *Div, grad, curl, and all that: an informal text on vector calculus*. WW Norton New York, 2005.
- [33] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman lectures on physics, Vols. I, II, & III: The new millennium edition*. Basic books, 2011, vol. 1,2,3.
- [34] W. C. Chew, *Waves and fields in inhomogeneous media*. IEEE press, 1995.
- [35] V. J. Katz, “The history of Stokes’ theorem,” *Mathematics Magazine*, vol. 52, no. 3, pp. 146–156, 1979.
- [36] W. K. Panofsky and M. Phillips, *Classical electricity and magnetism*. Courier Corporation, 2005.
- [37] T. Lancaster and S. J. Blundell, *Quantum field theory for the gifted amateur*. OUP Oxford, 2014.
- [38] W. C. Chew, “Fields and waves: Lecture notes for ECE 350 at UIUC,” <https://engineering.purdue.edu/wcchew/ece350.html>, 1990.
- [39] C. M. Bender and S. A. Orszag, *Advanced mathematical methods for scientists and engineers I: Asymptotic methods and perturbation theory*. Springer Science & Business Media, 2013.
- [40] J. M. Crowley, *Fundamentals of applied electrostatics*. Krieger Publishing Company, 1986.
- [41] C. Balanis, *Advanced Engineering Electromagnetics*. Hoboken, NJ, USA: Wiley, 2012.
- [42] J. D. Jackson, *Classical electrodynamics*. John Wiley & Sons, 1999.
- [43] R. Courant and D. Hilbert, *Methods of Mathematical Physics: Partial Differential Equations*. John Wiley & Sons, 2008.
- [44] L. Esaki and R. Tsu, “Superlattice and negative differential conductivity in semiconductors,” *IBM Journal of Research and Development*, vol. 14, no. 1, pp. 61–65, 1970.
- [45] E. Kudeki and D. C. Munson, *Analog Signals and Systems*. Upper Saddle River, NJ, USA: Pearson Prentice Hall, 2009.
- [46] A. V. Oppenheim and R. W. Schaffer, *Discrete-time signal processing*. Pearson Education, 2014.

- [47] R. F. Harrington, *Time-harmonic electromagnetic fields*. McGraw-Hill, 1961.
- [48] E. C. Jordan and K. G. Balmain, *Electromagnetic waves and radiating systems*. Prentice-Hall, 1968.
- [49] G. Agarwal, D. Pattanayak, and E. Wolf, "Electromagnetic fields in spatially dispersive media," *Physical Review B*, vol. 10, no. 4, p. 1447, 1974.
- [50] S. L. Chuang, *Physics of photonic devices*. John Wiley & Sons, 2012, vol. 80.
- [51] B. E. Saleh and M. C. Teich, *Fundamentals of photonics*. John Wiley & Sons, 2019.
- [52] M. Born and E. Wolf, *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light*. Elsevier, 2013.
- [53] R. W. Boyd, *Nonlinear optics*. Elsevier, 2003.
- [54] Y.-R. Shen, *The principles of nonlinear optics*. New York, Wiley-Interscience, 1984.
- [55] N. Bloembergen, *Nonlinear optics*. World Scientific, 1996.
- [56] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of electric machinery*. McGraw-Hill New York, 1986.
- [57] A. E. Fitzgerald, C. Kingsley, S. D. Umans, and B. James, *Electric machinery*. McGraw-Hill New York, 2003, vol. 5.
- [58] M. A. Brown and R. C. Semelka, *MRI.: Basic Principles and Applications*. John Wiley & Sons, 2011.
- [59] C. A. Balanis, *Advanced engineering electromagnetics*. John Wiley & Sons, 1999.
- [60] Wikipedia, "Lorentz force," https://en.wikipedia.org/wiki/Lorentz_force/, accessed: 2019-09-06.
- [61] R. O. Dendy, *Plasma physics: an introductory course*. Cambridge University Press, 1995.
- [62] P. Sen and W. C. Chew, "The frequency dependent dielectric and conductivity response of sedimentary rocks," *Journal of microwave power*, vol. 18, no. 1, pp. 95–105, 1983.
- [63] D. A. Miller, *Quantum Mechanics for Scientists and Engineers*. Cambridge, UK: Cambridge University Press, 2008.
- [64] W. C. Chew, "Quantum mechanics made simple: Lecture notes for ECE 487 at UIUC," <http://wcchew.ece.illinois.edu/chew/course/QMAll20161206.pdf>, 2016.
- [65] B. G. Streetman and S. Banerjee, *Solid state electronic devices*. Prentice hall Englewood Cliffs, NJ, 1995.

- [66] Smithsonian, “This 1600-year-old goblet shows that the romans were nanotechnology pioneers,” <https://www.smithsonianmag.com/history/this-1600-year-old-goblet-shows-that-the-romans-were-nanotechnology-pioneers-787224/>, accessed: 2019-09-06.
- [67] K. G. Budden, *Radio waves in the ionosphere*. Cambridge University Press, 2009.
- [68] R. Fitzpatrick, *Plasma physics: an introduction*. CRC Press, 2014.
- [69] G. Strang, *Introduction to linear algebra*. Wellesley-Cambridge Press Wellesley, MA, 1993, vol. 3.
- [70] K. C. Yeh and C.-H. Liu, “Radio wave scintillations in the ionosphere,” *Proceedings of the IEEE*, vol. 70, no. 4, pp. 324–360, 1982.
- [71] J. Kraus, *Electromagnetics*. McGraw-Hill, 1984.
- [72] Wikipedia, “Circular polarization,” https://en.wikipedia.org/wiki/Circular_polarization.
- [73] Q. Zhan, “Cylindrical vector beams: from mathematical concepts to applications,” *Advances in Optics and Photonics*, vol. 1, no. 1, pp. 1–57, 2009.
- [74] H. Haus, *Electromagnetic Noise and Quantum Optical Measurements*, ser. Advanced Texts in Physics. Springer Berlin Heidelberg, 2000.
- [75] W. C. Chew, “Lectures on theory of microwave and optical waveguides, for ECE 531 at UIUC,” <https://engineering.purdue.edu/wcchew/course/tqwAll20160215.pdf>, 2016.
- [76] L. Brillouin, *Wave propagation and group velocity*. Academic Press, 1960.
- [77] R. Plonsey and R. E. Collin, *Principles and applications of electromagnetic fields*. McGraw-Hill, 1961.
- [78] M. N. Sadiku, *Elements of electromagnetics*. Oxford University Press, 2014.
- [79] A. Wadhwa, A. L. Dal, and N. Malhotra, “Transmission media,” <https://www.slideshare.net/abhishekwadhw786/transmission-media-9416228>.
- [80] P. H. Smith, “Transmission line calculator,” *Electronics*, vol. 12, no. 1, pp. 29–31, 1939.
- [81] F. B. Hildebrand, *Advanced calculus for applications*. Prentice-Hall, 1962.
- [82] J. Schutt-Aine, “Experiment02-coaxial transmission line measurement using slotted line,” <http://emlab.uiuc.edu/ece451/ECE451Lab02.pdf>.
- [83] D. M. Pozar, E. J. K. Knapp, and J. B. Mead, “ECE 584 microwave engineering laboratory notebook,” http://www.ecs.umass.edu/ece/ece584/ECE584_lab_manual.pdf, 2004.
- [84] R. E. Collin, *Field theory of guided waves*. McGraw-Hill, 1960.

- [85] Q. S. Liu, S. Sun, and W. C. Chew, "A potential-based integral equation method for low-frequency electromagnetic problems," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 3, pp. 1413–1426, 2018.
- [86] M. Born and E. Wolf, *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light*. Pergamon, 1986, first edition 1959.
- [87] Wikipedia, "Snell's law," https://en.wikipedia.org/wiki/Snell's_law.
- [88] G. Tyras, *Radiation and propagation of electromagnetic waves*. Academic Press, 1969.
- [89] L. Brekhovskikh, *Waves in layered media*. Academic Press, 1980.
- [90] Scholarpedia, "Goos-hanchen effect," http://www.scholarpedia.org/article/Goos-Hanchen_effect.
- [91] K. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," in *Proceedings of the Institution of Electrical Engineers*, vol. 113, no. 7. IET, 1966, pp. 1151–1158.
- [92] E. Glytsis, "Slab waveguide fundamentals," http://users.ntua.gr/eglytsis/IO/Slab_Waveguides_p.pdf, 2018.
- [93] Wikipedia, "Optical fiber," https://en.wikipedia.org/wiki/Optical_fiber.
- [94] Atlantic Cable, "1869 indo-european cable," <https://atlantic-cable.com/Cables/1869IndoEur/index.htm>.
- [95] Wikipedia, "Submarine communications cable," https://en.wikipedia.org/wiki/Submarine_communications_cable.
- [96] D. Brewster, "On the laws which regulate the polarisation of light by reflexion from transparent bodies," *Philosophical Transactions of the Royal Society of London*, vol. 105, pp. 125–159, 1815.
- [97] Wikipedia, "Brewster's angle," https://en.wikipedia.org/wiki/Brewster's_angle.
- [98] H. Raether, "Surface plasmons on smooth surfaces," in *Surface plasmons on smooth and rough surfaces and on gratings*. Springer, 1988, pp. 4–39.
- [99] E. Kretschmann and H. Raether, "Radiative decay of non radiative surface plasmons excited by light," *Zeitschrift für Naturforschung A*, vol. 23, no. 12, pp. 2135–2136, 1968.
- [100] Wikipedia, "Surface plasmon," https://en.wikipedia.org/wiki/Surface_plasmon.
- [101] Wikimedia, "Gaussian wave packet," https://commons.wikimedia.org/wiki/File:Gaussian_wave_packet.svg.
- [102] Wikipedia, "Charles K. Kao," https://en.wikipedia.org/wiki/Charles_K._Kao.
- [103] H. B. Callen and T. A. Welton, "Irreversibility and generalized noise," *Physical Review*, vol. 83, no. 1, p. 34, 1951.

- [104] R. Kubo, "The fluctuation-dissipation theorem," *Reports on progress in physics*, vol. 29, no. 1, p. 255, 1966.
- [105] C. Lee, S. Lee, and S. Chuang, "Plot of modal field distribution in rectangular and circular waveguides," *IEEE transactions on microwave theory and techniques*, vol. 33, no. 3, pp. 271–274, 1985.
- [106] W. C. Chew, *Waves and Fields in Inhomogeneous Media*. IEEE Press, 1996.
- [107] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions: with formulas, graphs, and mathematical tables*. Courier Corporation, 1965, vol. 55.
- [108] —, "Handbook of mathematical functions: with formulas, graphs, and mathematical tables," <http://people.math.sfu.ca/~cbm/aands/index.htm>.
- [109] W. C. Chew, W. Sha, and Q. I. Dai, "Green's dyadic, spectral function, local density of states, and fluctuation dissipation theorem," *arXiv preprint arXiv:1505.01586*, 2015.
- [110] Wikipedia, "Very Large Array," https://en.wikipedia.org/wiki/Very_Large_Array.
- [111] C. A. Balanis and E. Holzman, "Circular waveguides," *Encyclopedia of RF and Microwave Engineering*, 2005.
- [112] M. Al-Hakkak and Y. Lo, "Circular waveguides with anisotropic walls," *Electronics Letters*, vol. 6, no. 24, pp. 786–789, 1970.
- [113] Wikipedia, "Horn Antenna," https://en.wikipedia.org/wiki/Horn_antenna.
- [114] P. Silvester and P. Benedek, "Microstrip discontinuity capacitances for right-angle bends, t junctions, and crossings," *IEEE Transactions on Microwave Theory and Techniques*, vol. 21, no. 5, pp. 341–346, 1973.
- [115] R. Garg and I. Bahl, "Microstrip discontinuities," *International Journal of Electronics Theoretical and Experimental*, vol. 45, no. 1, pp. 81–87, 1978.
- [116] P. Smith and E. Turner, "A bistable fabry-perot resonator," *Applied Physics Letters*, vol. 30, no. 6, pp. 280–281, 1977.
- [117] A. Yariv, *Optical electronics*. Saunders College Publ., 1991.
- [118] Wikipedia, "Klystron," <https://en.wikipedia.org/wiki/Klystron>.
- [119] —, "Magnetron," https://en.wikipedia.org/wiki/Cavity_magnetron.
- [120] —, "Absorption Wavemeter," https://en.wikipedia.org/wiki/Absorption_wavemeter.
- [121] W. C. Chew, M. S. Tong, and B. Hu, "Integral equation methods for electromagnetic and elastic waves," *Synthesis Lectures on Computational Electromagnetics*, vol. 3, no. 1, pp. 1–241, 2008.
- [122] A. D. Yaghjian, "Reflections on maxwell's treatise," *Progress In Electromagnetics Research*, vol. 149, pp. 217–249, 2014.

- [123] L. Nagel and D. Pederson, "Simulation program with integrated circuit emphasis," in *Midwest Symposium on Circuit Theory*, 1973.
- [124] S. A. Schelkunoff and H. T. Friis, *Antennas: theory and practice*. Wiley New York, 1952, vol. 639.
- [125] H. G. Schantz, "A brief history of uwb antennas," *IEEE Aerospace and Electronic Systems Magazine*, vol. 19, no. 4, pp. 22–26, 2004.