

Lecture 28

Different Types of Antennas—Heuristics

28.1 Types of Antennas

There are different types of antennas for different applications [128]. We will discuss their functions heuristically in the following discussions.

28.1.1 Resonance Tunneling in Antenna

A simple antenna like a short dipole behaves like a Hertzian dipole with an effective length. A short dipole has an input impedance resembling that of a capacitor. Hence, it is difficult to drive current into the antenna unless other elements are added. Hertz used two metallic spheres to increase the current flow. When a large current flows on the stem of the Hertzian dipole, the stem starts to act like inductor. Thus, the end cap capacitances and the stem inductance together can act like a resonator enhancing the current flow on the antenna.

Some antennas are deliberately built to resonate with its structure to enhance its radiation. A half-wave dipole is such an antenna as shown in Figure 28.1 [124]. One can think that these antennas are using resonance tunneling to enhance their radiation efficiencies. A half-wave dipole can also be thought of as a flared open transmission line in order to make it radiate. It can be gradually morphed from a quarter-wavelength transmission line as shown in Figure 28.1. A transmission is a poor radiator, because the electromagnetic energy is trapped between two pieces of metal. But a flared transmission line can radiate its field to free space. The dipole antenna, though a simple device, has been extensively studied by King [129]. He has reputed to have produced over 100 PhD students studying the dipole antenna.

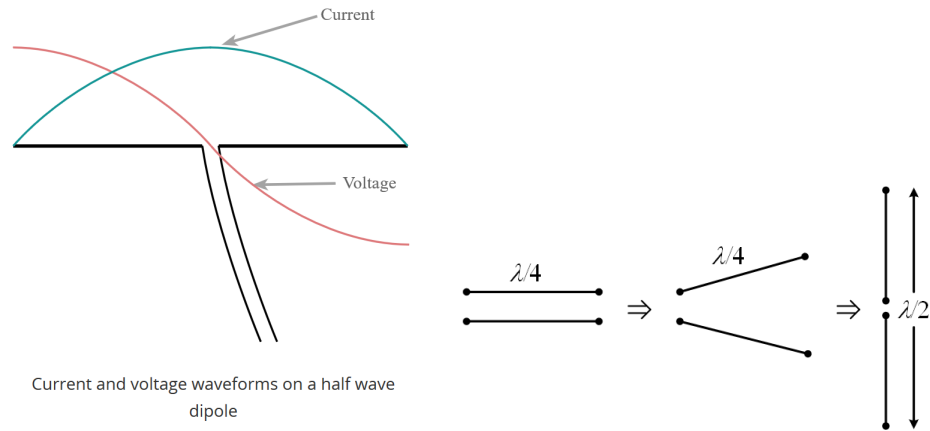


Figure 28.1: A half-wave dipole can be thought of as a resonator. It can be thought of as a quarter-wavelength transmission line that is gradually opened up (courtesy of electronics-notes.com).

The disadvantage of a half-wave dipole is that it has to be at least about half a wavelength before it radiates well. Engineers are creative, and they invent the folded dipole. For antennas of the same size, a folded dipole can resonate at a lower frequency because the current does not stop abruptly at its two ends. Figure 28.2 shows a Yagi-Uda antenna driven by a folded dipole.

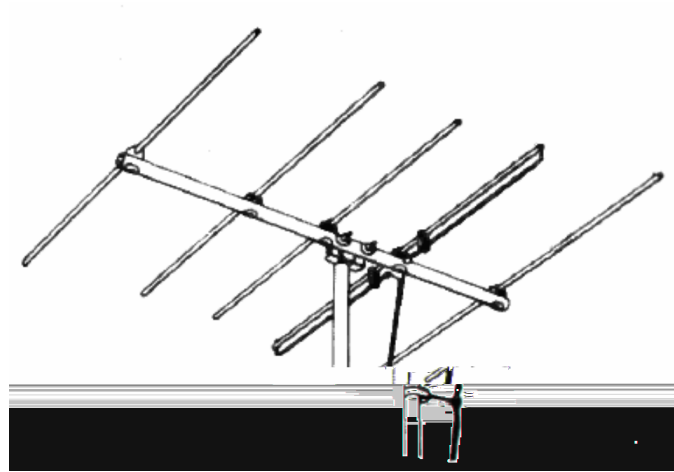


Figure 28.2: In a Yagi-Uda antenna, when a wire antenna is less than half a wavelength, it acts as a waveguide, or a director. Then the wire antenna is slightly more than half a wavelength, it acts as a reflector [130]. Therefore, the antenna radiates predominantly in one direction (courtesy of Wikipedia [131]).

A Yagi-Uda antenna is also another interesting invention. It was invented in 1926 by Yagi and Uda in Japan by plainly using physical intuition [130]. Physical intuition was a tool of engineers of yesteryears while modern engineers tend to use sophisticated computer design software. Surprisingly, the elements of dipoles in front of the driver element are acting like a waveguide in space, while the element at the back acts like a reflector. Therefore, the field radiated by the driver element will be directed toward the front of the antenna. Thus, this antenna has higher directivity than just a stand alone dipole. Due to its simplicity, this antenna has been made into nano-antennas which can radiate at optical frequencies.

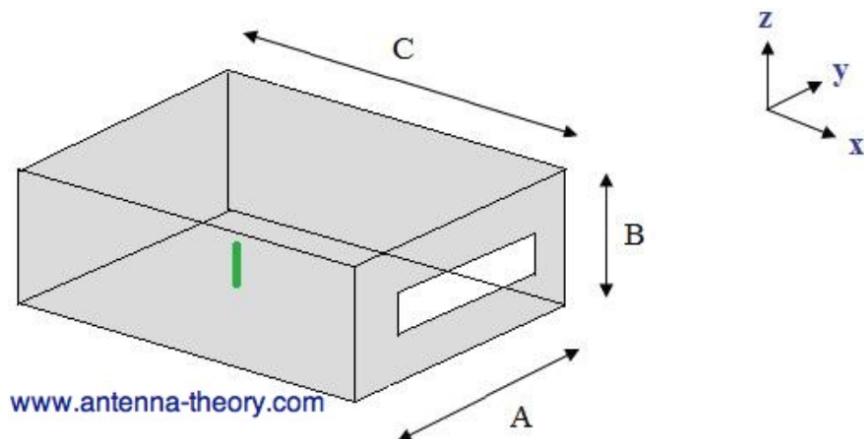


Figure 28.3: A cavity-backed slot antenna radiates well because when the small dipole radiates close to the resonant frequency of the cavity, the field strength is strong inside the cavity, and hence around the slot (courtesy of antenna-theory.com).

Slot antenna is a simple antenna to make [132]. To improve the radiation efficiency of slot antenna, it is made to radiate via a cavity. A cavity-backed slot antenna that uses such a concept and this is shown in Figure 28.3. A small dipole with poor radiation efficiency is placed inside the cavity. When the operating frequency is close to the resonant frequency of the cavity, the field strength inside the cavity becomes strong, and much of the energy can leak from the cavity via the slot on its side. This makes the antenna radiate more efficiently into free space compared to just the small dipole alone.

Another antenna that resembles a cavity backed slot antenna is the patch antenna, or microstrip patch antenna. This is shown in Figure 28.4. This antenna also radiates efficiently by resonant tunneling. The resonant frequency of the patch antenna (top of Figure 28.4) is roughly when L is half a wavelength. This is similar to the resonant frequency of a transmission line with open circuit at both ends. The current sloshes back and forth across the length of the patch antenna along the L direction. The second design (bottom of Figure 28.4) has an inset feed. This allows the antenna to resonate at a lower frequency because the current has a longer path to slosh through when it is at resonance.

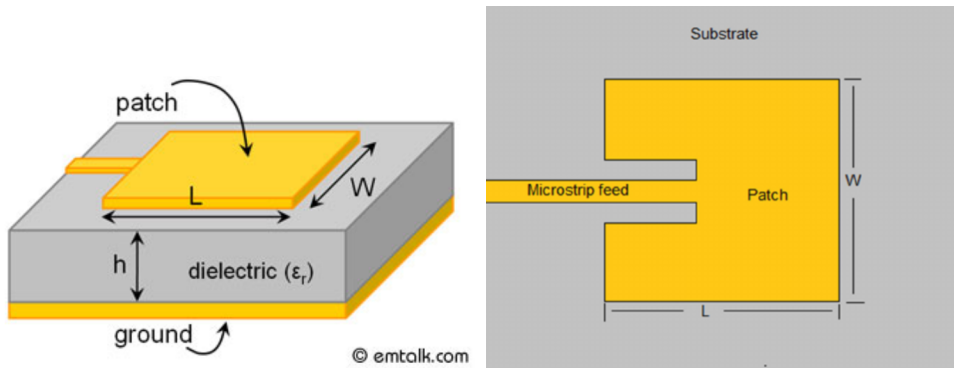


Figure 28.4: A patch antenna also radiates well when it resonates. The patch antenna resembles a cavity resonator with magnetic wall (courtesy of emtalk.com).

28.1.2 Horn Antennas

The impedance of space is 377 ohms while that of most transmission line is 50 ohms. This mismatch can be mitigated by using a flared horn (see Figure 28.5) [133].

One can think that the characteristic impedance of a transmission line made of two pieces of metal as $Z_0 = \sqrt{L/C}$. As the horn flares, C becomes smaller, increasing its characteristic impedance to get close to that of free space. This allows for better impedance matching from the source to free space.

A corrugated horn, as we have discussed previously in a circular waveguide, discourages current flows in the non-axial symmetric mode. It encourages the propagation of the TE_{01} mode in the circular waveguide and hence, the circular horn antenna. This mode is axially symmetric. Hence, this antenna can radiate fields that are axially symmetric [134, 135].

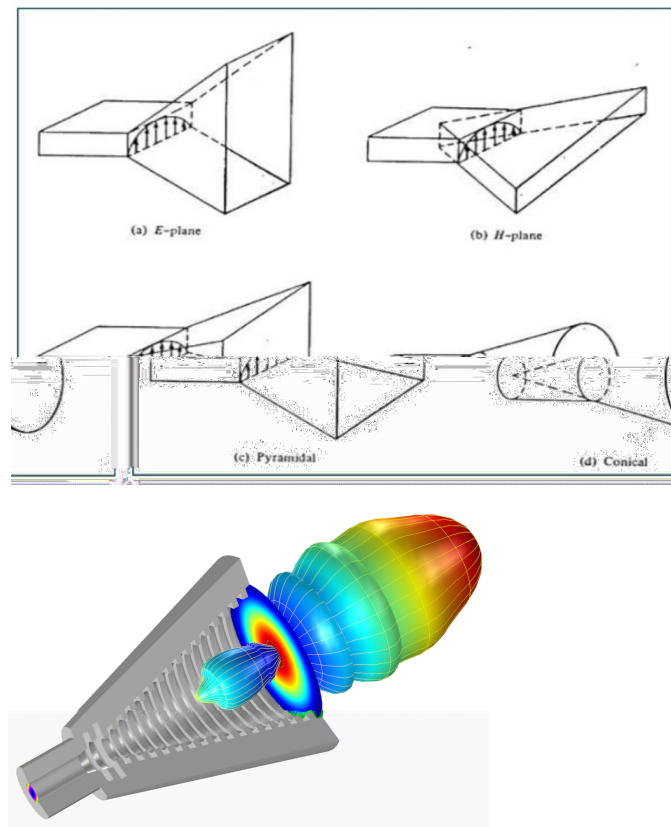


Figure 28.5: A horn antenna works with the same principle as the biconical antenna. Its flared horn changes the waveguide impedance so as to match from that of a waveguide to that of free space. The lower figure is that of a corrugated circular horn antenna. The corrugation enhances the propagation of the TE_{01} mode in the circular waveguide, and hence, the cylindrical symmetry of the mode (courtesy of tutorialpoints.com and comsol.com).

A Vivaldi antenna (invented by P. Gibson in 1978 [136]), is shown in Figure 28.6. It is also called a notch antenna. It works by the same principle to gradually match the impedance of the source to that of free space. But such a gradually flared horn has the element of a frequency independent antenna. The low frequency component of the signal will radiate from the wide end of the flared notch, while the high frequency component will radiate from the narrow end of the notch. Thus, this antenna can radiate well over a broad range of frequencies, and this gives the antenna a broad bandwidth performance. It is good for transmitting a pulsed signal which has a broad frequency spectrum.

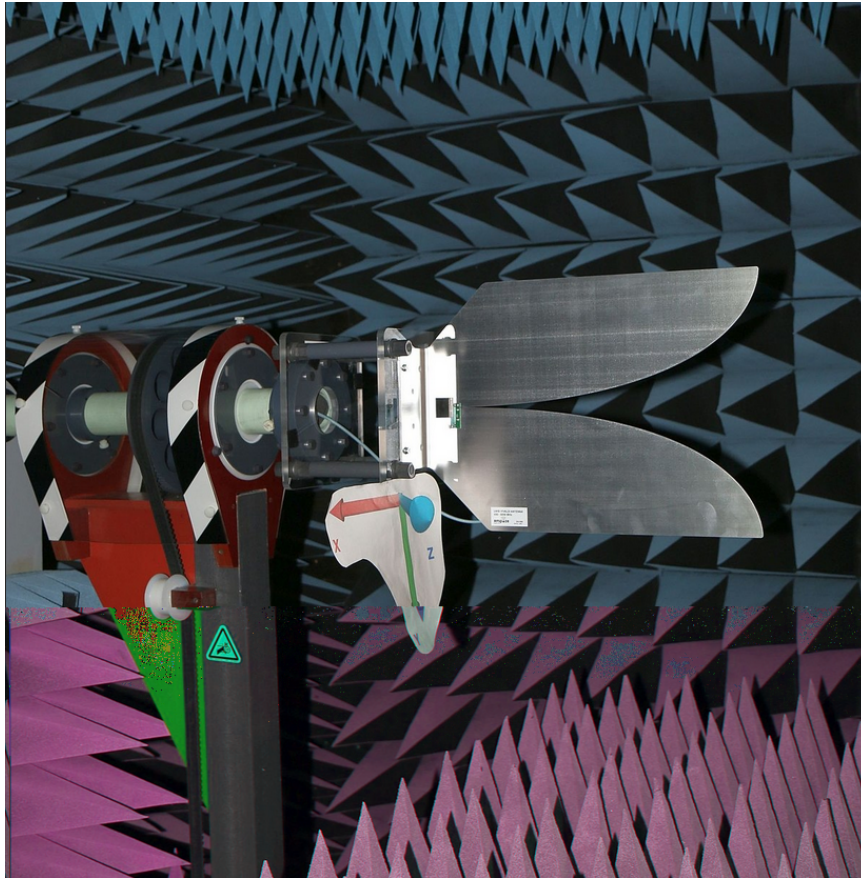


Figure 28.6: A Vivaldi antenna works iike a horn antenna, but uses very little metal. Hence, it is cheap to build (courtesy of Wikipedia [137]).

28.1.3 Quasi-Optical Antennas

High-frequency or short wavelength electromagnetic field behaves like light ray as in optics. Therefore, many high-frequency antennas are designed based on the principle of ray optics. A reflector antenna is such an antenna as shown in Figure 28.7. The reflector antenna in this case is a Cassegrain design [138]¹ where a sub-reflector is present. This allows the antenna to be fed from behind the parabolic dish where the electronics can be stored and isolated as well. Reflector antennas [140] is used a lot in radio astronomy and space exploration due to their high directivity and sensitivity.

¹The name came from an optical telescope of similar design [139]

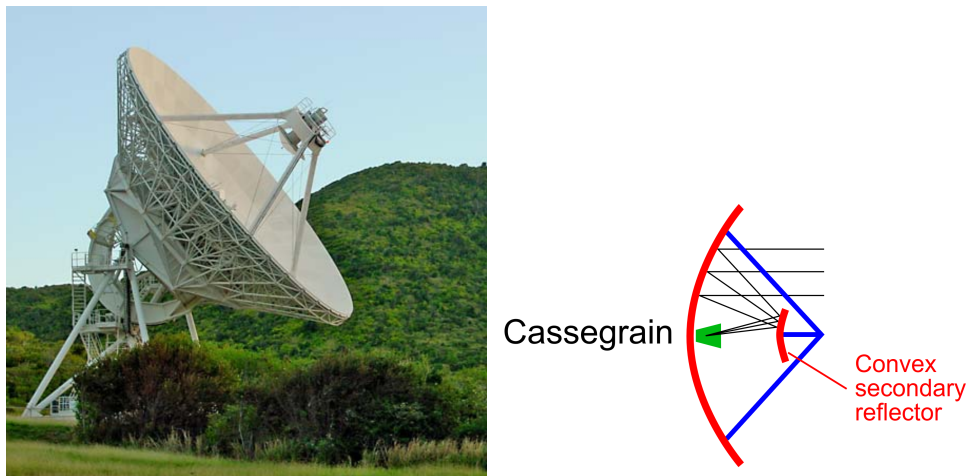


Figure 28.7: The top picture of an NRAO radio telescope antenna of Cassegrain design (courtesy of Britannica.com). The bottom is the detail of the Cassegrain design (courtesy of rev.com).

Another recent invention is the reflectarray antenna [141, 142] which is very popular. One of them is as shown in Figure 28.8. Due to recent advent in simulation technology, complicated structures can be simulated on a computer, including one with a complicated surface design. Patch elements can be etched onto a flat surface as shown, giving it effective impedance that is spatially varying, making it reflect like a curved surface. Such a surface is known as a meta-surface [143, 144]. It can greatly economize on the space of a reflector antenna.

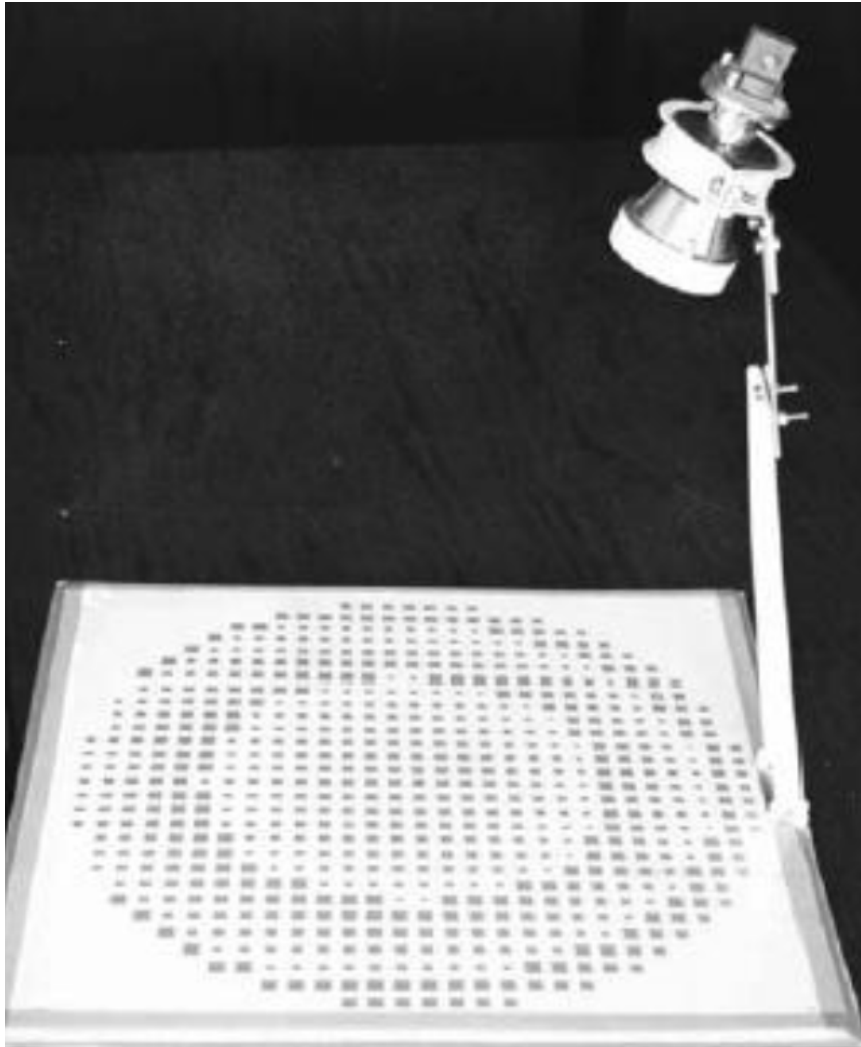


Figure 28.8: A reflectarray where the reflector is a flat surface. Patches are unequally spaced to give the array the focussing effect (courtesy of antenna-theory.com).

Another quasi-optical antenna is the lens antenna as shown in Figure 28.9 [145]. The design of this antenna follows lens optics, and is only valid when the wavelength is very short compared to the curvature of the surfaces. In this case, reflection and transmission at a curve surface is similar to that of a flat surface. This is called the tangent-plane approximation of a curve surface, and is valid at high frequencies.

.

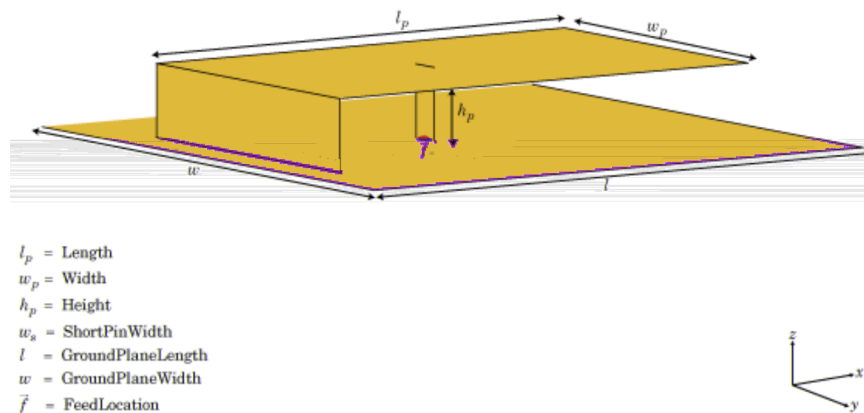


Figure 28.10: A PIFA (planar inverted F antenna) is compact, broadband, and easy to fabricate. It is good for cell phone antennas due to its small size (courtesy of Mathworks).

An interesting small antenna is the U-slot antenna shown in Figure 28.11 [147,148]. Because the current is forced to follow a longer path by the U-slot, it has a lower resonant frequency and hence, can be made smaller. In order to give the antenna a larger bandwidth, its Q is made smaller by etching it on a thick dielectric substrate (shown as the dielectric material region in the figure). But feeding it with a longer probe will make the bandwidth of the antenna smaller, due to the larger inductance of the probe. An ingenious invention is to use an L probe [149]. The L probe has an inductive part as well as a capacitive part. Their reactance cancel each other, allowing the electromagnetic energy to tunnel through the antenna, making it a better radiator.

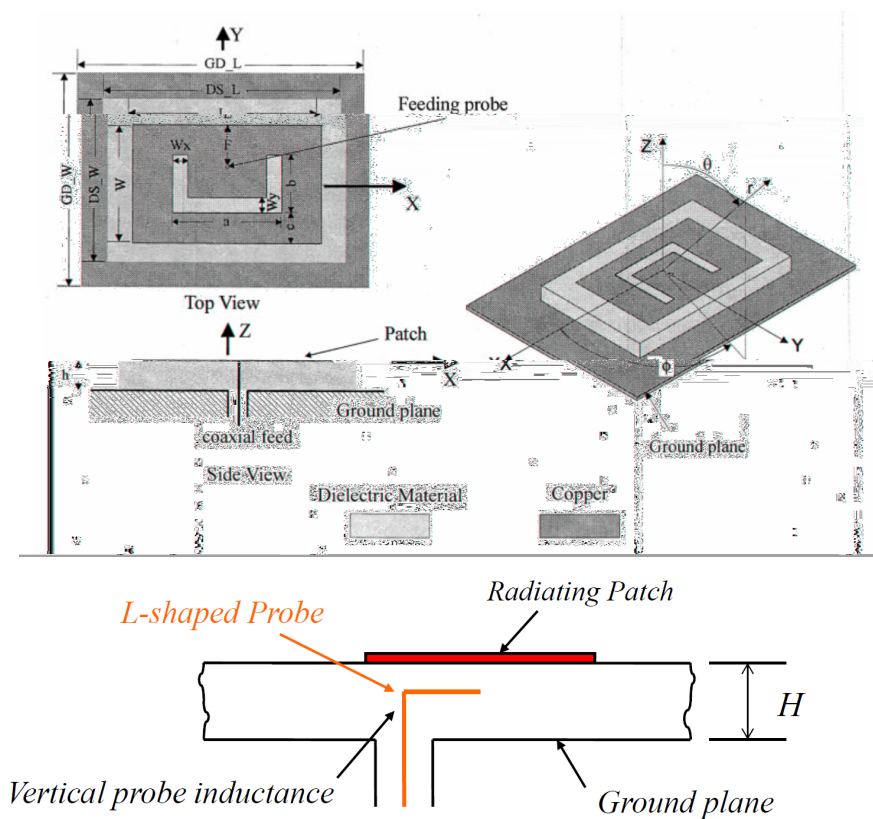


Figure 28.11: The top figure shows a U slot patch antenna design. The bottom figure shows a patch antenna fed by an L probe with significant increase in bandwidth (courtesy of K.M. Luk) [149].

Another area where small antennas are needed is in RFID (radio frequency identification) tag [150]. Since tags are placed outside the packages of products, an RFID tag has a transmit-receive antenna which can talk to a small computer chip where data about the package can be stored. An RFID reader can quickly communicate with the RFID tag to retrieve information about the package. Such a small antenna design for RFID tag is shown in Figure 28.12. It uses image theorem so that the antenna can be made half as small. Then slots are cut into the radiating patch, so that the current follows a longer path. This lowers the resonant frequency of the antenna, allowing it to be made smaller.

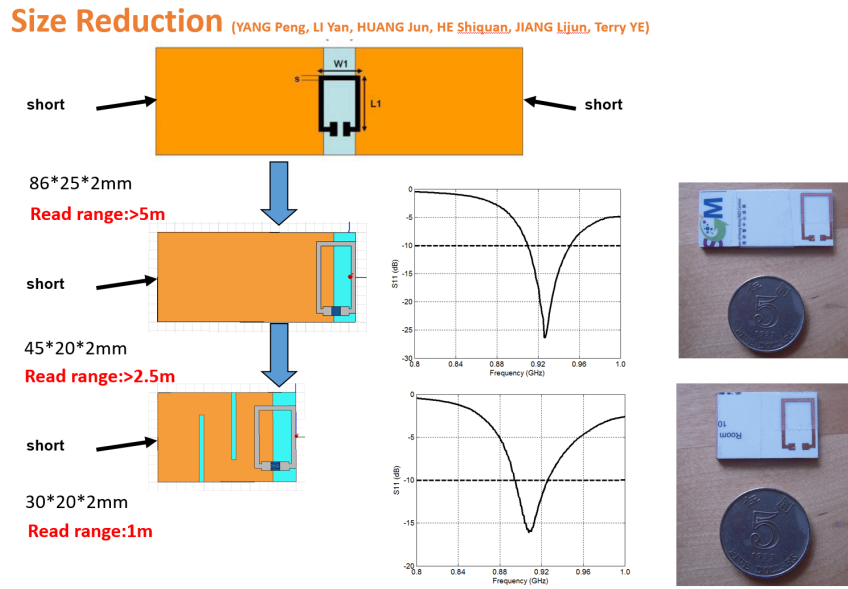


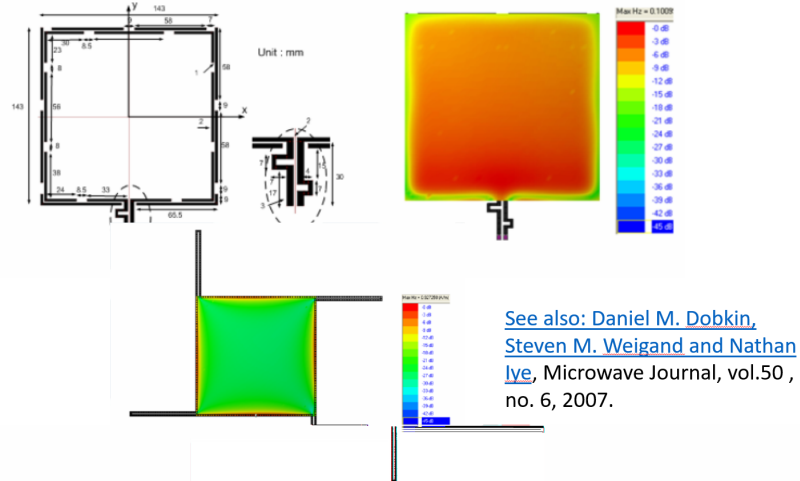
Figure 28.12: Some RFID antennas designed at The University of Hong Kong (courtesy of P. Yang, Y. Li, J. Huang, L.J. Jiang, S.Q. He, T. Ye, and W.C. Chew).

An RFID reader can be designed to read the information from a batch of vials or tubes containing different chemicals. Hence, a large loop antenna is needed at a sufficiently high frequency (for large bandwidth). However, driving a loop antenna at a sufficiently high frequency will result in a non-constant current around the loop. (Fundamentally, this comes from the retardation effect of electromagnetic field.) This will result in a non-uniform field inside the loop defeating the design of the RFID reader.

One way to view how the non-uniform current come about is that a piece of wire becomes a tiny inductor. Across an inductor, $V = j\omega LI$, implying a 90° phase shift between the voltage and the current. In other words, the voltage drop is always nonzero, and hence, the voltage cannot be constant around the loop. Since the voltage and current are locally related by the local inductance, the current cannot be constant also.

To solve the problem of the current and voltage being non-constant around the loop, the local inductor is connected in series with a capacitor [151]. This causes them to resonate. At resonance, the current-voltage relationship across the tank circuit is such that there is no voltage drop across the tank circuit. In this case, the voltage becomes uniform across the loop so is the current. Therefore, one way to enable a uniform current in a large loop is to capacitively load the loop. This will ensure a constant phase, or a more uniform current around the loop, and hence, a more efficient reader. Such a design is shown in Figure 28.13.

Square Segmented Loop



By CHEN Zhi Ning, from ASTAR, Singapore, 2009

Current Distribution and Measured S11

(YANG Peng, LI Yan, HUANG Jun, HE Shiquan, JIANG Lijun, Terry YE)

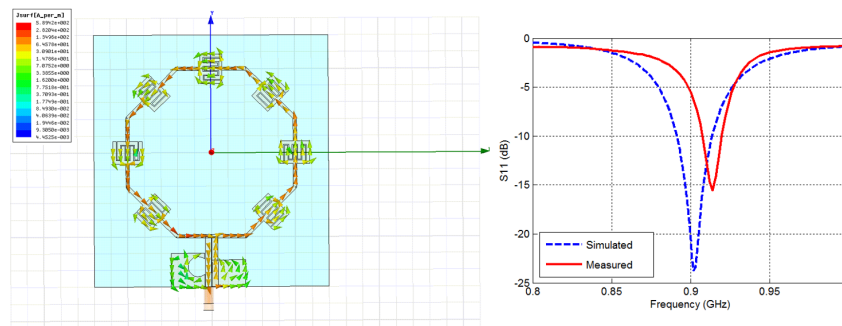


Figure 28.13: The top figure shows a RFID reader designed by [152]. The bottom figure shows simulation and measurement done at The University of Hong Kong (courtesy of Z.N. Chen [152] and P. Yang, Y. Li, J. Huang, L.J. Jiang, S.Q. He, T. Ye, and W.C. Chew).

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, Bell’s 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, also 1965, 1984.
- [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, also 1990.
- [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, also 1989.
- [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, also 1953, 1973, 1981.
- [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.
- [126] E. Kudeki, "Fields and Waves," <http://remote2.ece.illinois.edu/~erhan/FieldsWaves/ECE350lectures.html>.
- [127] Wikipedia, "Antenna Aperture," https://en.wikipedia.org/wiki/Antenna_aperture.
- [128] C. A. Balanis, *Antenna theory: analysis and design*. John Wiley & Sons, 2016.
- [129] R. W. P. King, G. S. Smith, M. Owens, and T. Wu, "Antennas in matter: Fundamentals, theory, and applications," *NASA STI/Recon Technical Report A*, vol. 81, 1981.
- [130] H. Yagi and S. Uda, "Projector of the sharpest beam of electric waves," *Proceedings of the Imperial Academy*, vol. 2, no. 2, pp. 49–52, 1926.
- [131] Wikipedia, "Yagi-Uda Antenna," https://en.wikipedia.org/wiki/Yagi-Uda_antenna.
- [132] Antenna-theory.com, "Slot Antenna," <http://www.antenna-theory.com/antennas/aperture/slot.php>.
- [133] A. D. Olver and P. J. Clarricoats, *Microwave horns and feeds*. IET, 1994, vol. 39.
- [134] B. Thomas, "Design of corrugated conical horns," *IEEE Transactions on Antennas and Propagation*, vol. 26, no. 2, pp. 367–372, 1978.
- [135] P. J. B. Clarricoats and A. D. Olver, *Corrugated horns for microwave antennas*. IET, 1984, no. 18.
- [136] P. Gibson, "The vivaldi aerial," in *1979 9th European Microwave Conference*. IEEE, 1979, pp. 101–105.
- [137] Wikipedia, "Vivaldi Antenna," https://en.wikipedia.org/wiki/Vivaldi_antenna.
- [138] —, "Cassegrain Antenna," https://en.wikipedia.org/wiki/Cassegrain_antenna.
- [139] —, "Cassegrain Reflector," https://en.wikipedia.org/wiki/Cassegrain_reflector.
- [140] W. A. Imbriale, S. S. Gao, and L. Boccia, *Space antenna handbook*. John Wiley & Sons, 2012.
- [141] J. A. Encinar, "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 10, pp. 1403–1410, 2001.
- [142] D.-C. Chang and M.-C. Huang, "Microstrip reflectarray antenna with offset feed," *Electronics Letters*, vol. 28, no. 16, pp. 1489–1491, 1992.

- [143] G. Minatti, M. Faenzi, E. Martini, F. Caminita, P. De Vita, D. González-Ovejero, M. Sabbadini, and S. Maci, “Modulated metasurface antennas for space: Synthesis, analysis and realizations,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1288–1300, 2014.
- [144] X. Gao, X. Han, W.-P. Cao, H. O. Li, H. F. Ma, and T. J. Cui, “Ultrawideband and high-efficiency linear polarization converter based on double v-shaped metasurface,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 8, pp. 3522–3530, 2015.
- [145] D. De Schweinitz and T. L. Frey Jr, “Artificial dielectric lens antenna,” Nov. 13 2001, US Patent 6,317,092.
- [146] K.-L. Wong, “Planar antennas for wireless communications,” *Microwave Journal*, vol. 46, no. 10, pp. 144–145, 2003.
- [147] H. Nakano, M. Yamazaki, and J. Yamauchi, “Electromagnetically coupled curl antenna,” *Electronics Letters*, vol. 33, no. 12, pp. 1003–1004, 1997.
- [148] K. Lee, K. Luk, K.-F. Tong, S. Shum, T. Huynh, and R. Lee, “Experimental and simulation studies of the coaxially fed U-slot rectangular patch antenna,” *IEE Proceedings-Microwaves, Antennas and Propagation*, vol. 144, no. 5, pp. 354–358, 1997.
- [149] K. Luk, C. Mak, Y. Chow, and K. Lee, “Broadband microstrip patch antenna,” *Electronics letters*, vol. 34, no. 15, pp. 1442–1443, 1998.
- [150] M. Bolic, D. Simplot-Ryl, and I. Stojmenovic, *RFID systems: research trends and challenges*. John Wiley & Sons, 2010.
- [151] D. M. Dobkin, S. M. Weigand, and N. Iyer, “Segmented magnetic antennas for near-field UHF RFID,” *Microwave Journal*, vol. 50, no. 6, p. 96, 2007.
- [152] Z. N. Chen, X. Qing, and H. L. Chung, “A universal UHF RFID reader antenna,” *IEEE transactions on microwave theory and techniques*, vol. 57, no. 5, pp. 1275–1282, 2009.
- [153] C.-T. Chen, *Linear system theory and design*. Oxford University Press, Inc., 1998.
- [154] S. H. Schot, “Eighty years of Sommerfeld’s radiation condition,” *Historia mathematica*, vol. 19, no. 4, pp. 385–401, 1992.
- [155] A. Ishimaru, *Electromagnetic wave propagation, radiation, and scattering from fundamentals to applications*. Wiley Online Library, 2017, also 1991.
- [156] A. E. H. Love, “I. the integration of the equations of propagation of electric waves,” *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, vol. 197, no. 287-299, pp. 1–45, 1901.
- [157] Wikipedia, “Christiaan Huygens,” https://en.wikipedia.org/wiki/Christiaan_Huygens.
- [158] —, “George Green (mathematician),” [https://en.wikipedia.org/wiki/George_Green_\(mathematician\)](https://en.wikipedia.org/wiki/George_Green_(mathematician)).

- [159] C.-T. Tai, *Dyadic Green's Functions in Electromagnetic Theory*. PA: International Textbook, Scranton, 1971.
- [160] —, *Dyadic Green functions in electromagnetic theory*. Institute of Electrical & Electronics Engineers (IEEE), 1994.
- [161] W. Franz, “Zur formulierung des huygensschen prinzipts,” *Zeitschrift für Naturforschung A*, vol. 3, no. 8-11, pp. 500–506, 1948.
- [162] J. A. Stratton, *Electromagnetic Theory*. McGraw-Hill Book Company, Inc., 1941.
- [163] J. D. Jackson, *Classical Electrodynamics*. John Wiley & Sons, 1962.
- [164] W. Meissner and R. Ochsenfeld, “Ein neuer effekt bei eintritt der supraleitfähigkeit,” *Naturwissenschaften*, vol. 21, no. 44, pp. 787–788, 1933.
- [165] Wikipedia, “Superconductivity,” <https://en.wikipedia.org/wiki/Superconductivity>.
- [166] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, “High-impedance electromagnetic surfaces with a forbidden frequency band,” *IEEE Transactions on Microwave Theory and techniques*, vol. 47, no. 11, pp. 2059–2074, 1999.