LECTURE 1: Introduction into Antenna Studies

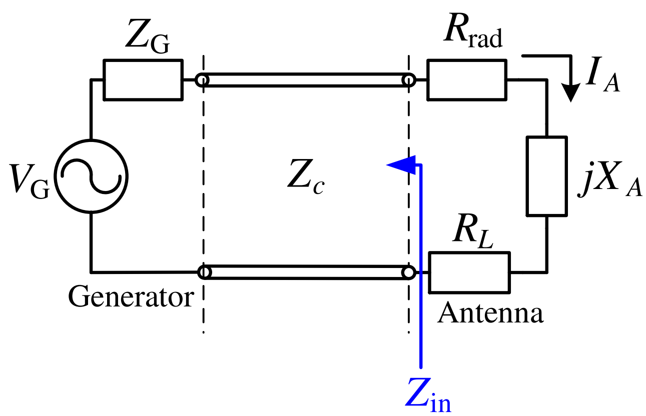
(*Definition and circuit theory description. Brief historical notes. General review of antenna geometries and arrangements. Wireless vs. cable communication systems. The radio-frequency spectrum.*)

1. Definition and circuit theory description

The antenna (aerial, EM radiator) is a device, which radiates or receives electromagnetic waves.

The antenna is the transition between a guiding device (transmission line, waveguide) and free space (or another usually unbounded medium). Its purpose is ***to convert the energy of a guided wave into the energy of a free-space wave (or vice versa) efficiently while at the same time the radiated power has a certain desired pattern of distribution in space***. At lower frequencies, where the cross-section of the transmission line is negligible relative to the wavelength (TEM transmission lines such as coaxial and twin-lead cables, microstrip and coplanar waveguide printed lines), we can view the antenna as a **device that converts free-space EM waves into voltage/current signals or *vice versa***.

a) Thevenin equivalent circuit of a radiating (transmitting, Tx) antenna



V_G - voltage-source generator (transmitter)

Z_G - impedance of the generator (transmitter)

Z_c - characteristic impedance of the connecting TL

R_{rad} - radiation resistance (relates to the radiated power as $P_{rad} = I_A^2 \cdot R_{rad}$)

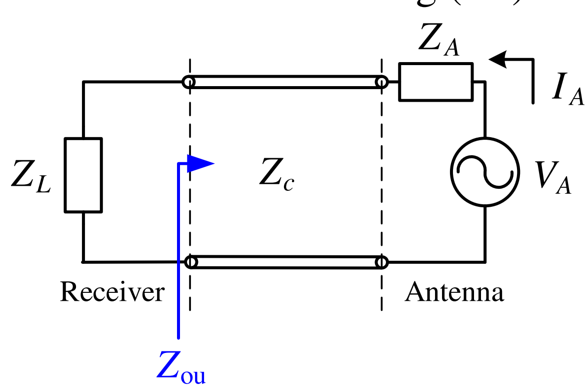
R_L - loss resistance (related to conduction and dielectric losses)

jX_A - antenna reactance
Z_{in} - input impedance of feed network as seen from antenna terminals
$Z_A = (R_{\text{rad}} + R_L) + jX_A$ - antenna impedance

One of the most important tasks in antenna design is the impedance matching of the antenna to the transmission line (TL) and the generator ($Z_A = Z_{\text{in}}^*$). Matching is often measured in terms of the voltage standing-wave ratio (VSWR or just SWR). Standing waves are avoided in high-power RF systems (radar, broadcasting) because they may cause arching or discharge in the TL. But the main benefit of good impedance match (with low SWR) is the maximum power transfer to/from the antenna.

Minimizing conduction (metals) and polarization (dielectric) loss (represented by R_L in Thevenin's equivalent) is also desirable. The losses decrease the efficiency of the antenna. On the other hand, in special applications such as ultra-wideband (UWB) antennas in imaging and radar, the antenna resistance may be increased intentionally in order to improve the bandwidth and suppress "ringing" in the transmitted or received signals.

b) Thevenin equivalent circuit of a receiving (Rx) antenna



Z_{ou} - output impedance of the antenna-plus-feed network, which serves as a signal generator as seen from the receiver terminals

The antenna is a critical component in a wireless communication system. A good design of the antenna can relax the system requirements and improve its overall performance.

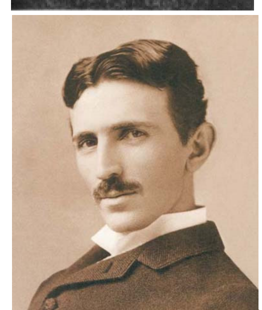
2. Brief historical notes

- James Clerk Maxwell formulates the mathematical model of electromagnetism (classical electro-dynamics), "*A Treatise on Electricity and Magnetism*", 1873. He shows that light is an electromagnetic (EM) wave, and that all EM waves propagate through space with the same speed, the speed of light.

- Heinrich Rudolph Hertz demonstrates in 1886 the first wireless EM wave system: a $\lambda/2$-dipole is excited with a spark; it radiates predominantly at $\lambda \approx 8$ m; a spark appears in the gap of a receiving loop some 20 m away. In 1890, he publishes his memoirs on electrodynamics, replacing all potentials by field strengths[1].

- May 7, 1895, a telegraph communication link is demonstrated by the Russian scientist, Alexander Popov. A message is sent from a Russian Navy ship 30 miles out in sea, all the way to his lab in St. Petersburg, Russia. This accomplishment is little known today.

- In 1892, Tesla delivers a presentation at the IRE of London about "transmitting intelligence without wires," and, in 1895, he transmits signals detected 80 km away. His patent on wireless links precedes that of Marconi.



- Guglielmo Marconi sends signals over large distances and successfully commercializes wireless communication systems. In 1901, he performs the first transatlantic transmission from Poldhu in Cornwall, England, to Newfoundland, Canada. He receives the Nobel prize for his work in 1909.

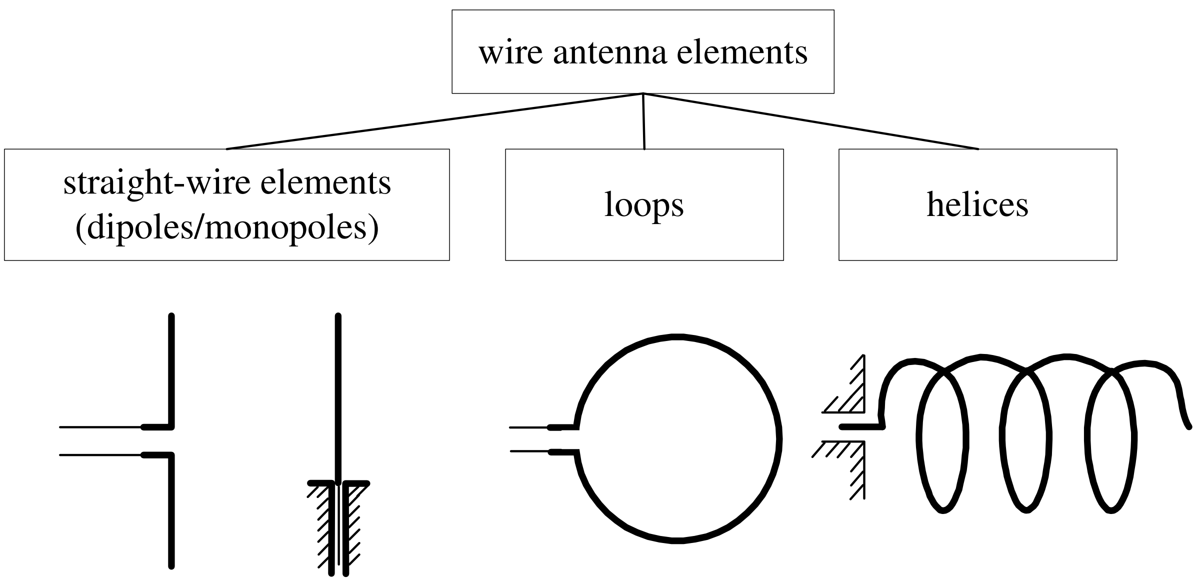
[1] Similar work on replacing the EM vector/scalar potentials with field vectors is done at about the same time by the English scientist Oliver Heaviside.

- The beginning of 20th century (until WW2) marks the boom in wire-antenna technology (dipoles and loops) and in wireless technology as a whole, which is largely due to the invention of the DeForest triode tube, used as a radio-frequency (RF) generator. Radio links are realized up to UHF (about 500 MHz) and over thousands of kilometers.
- WW2 marks a new era in wireless communications and antenna technology. The invention of new microwave generators (magnetrons and klystrons) leads to the development of the microwave antennas such as waveguide apertures, horns, reflectors, etc. It also marks the advent of radar detection and imaging.

3. General review of antenna geometries and arrangements

3.1. Single-element radiators

A. Wire radiators (single-element)



There is a variety of shapes corresponding to each group. For example, loops can be circular, square, rhombic, etc. Wire antennas are simple to make but their dimensions are commensurable with a wavelength. This limits the frequency range of their applicability. At low frequencies, these antennas become increasingly large. At very high frequencies, they are very small and the parasitics become difficult to control.

B. Aperture antennas (single element)


(Q-par Angus)

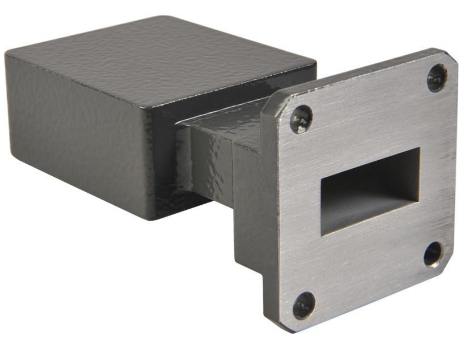
(a) pyramidal horn

Aperture antennas were developed before and during WW2 together with waveguide technology. Waveguides were primarily developed to transfer high-power microwave signals (cm wavelengths), generated by high-power sources such as magnetrons and klystrons. These types of antennas are preferable in the frequency range from 1 to 20 GHz.

[Radiometer Physics Gmbh]

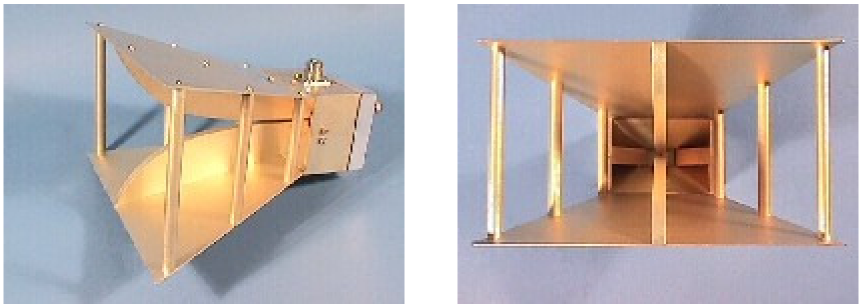
(b) conical horn

www.quinstar.com



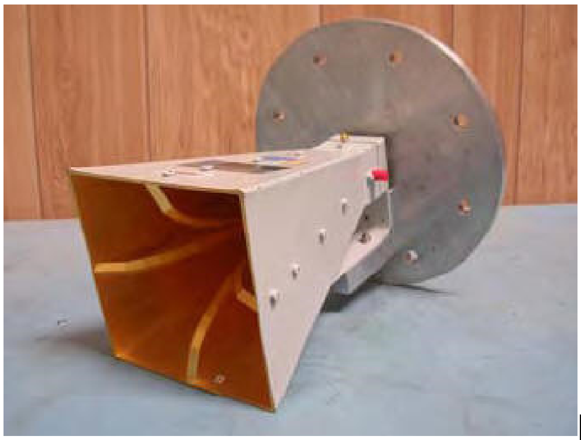
www.labvolt.com

(c) open rectangular waveguides



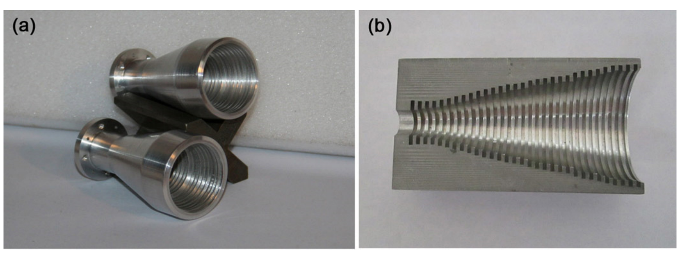
[Quinstar Technology Inc.]

(d) double-ridge horns (TEM, linear polarization, ultra-wide band)

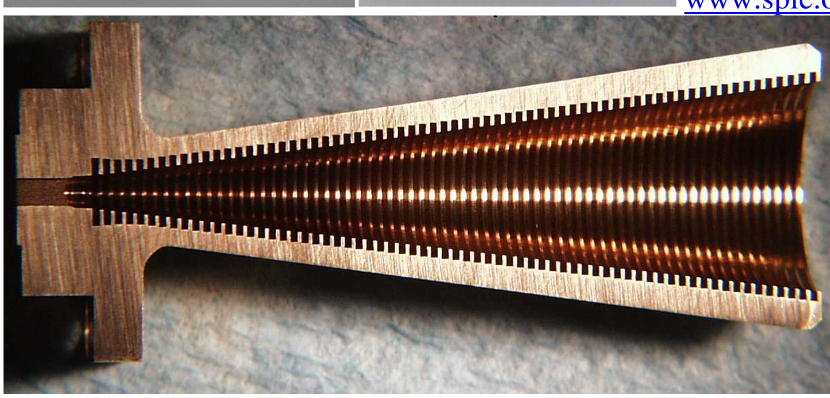


[TMC Design Corp.]

(e) quad-ridge horns (TEM, dual linear polarization allowing for many types of polarization depending on feed, ultra-wide band)



www.spie.org



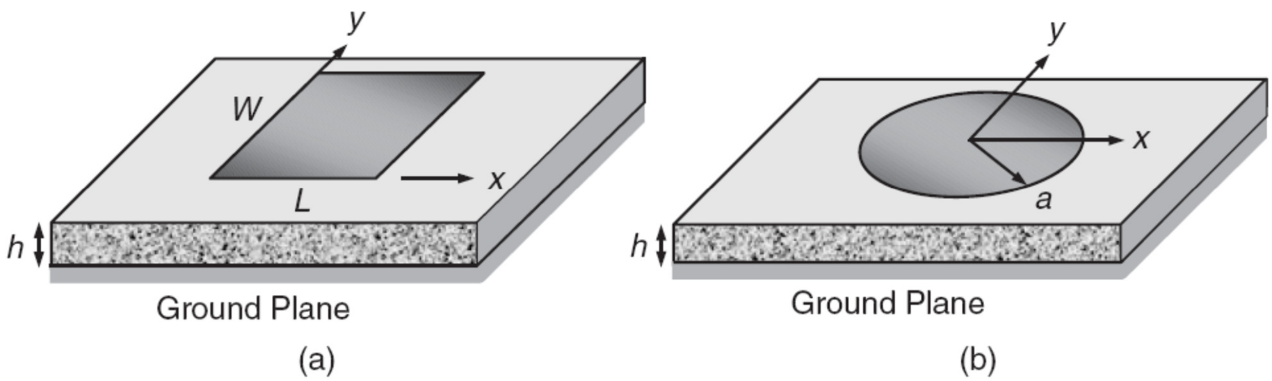
[ZAX Millimeter Wave Corp.]

(f) corrugated horns (symmetric patterns, low side lobes, low cross-polarization), often used as primary feeds in reflector antennas

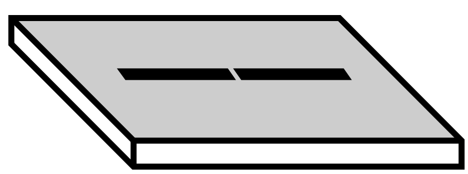
C. Printed antennas

The patch antennas consist of a metallic pattern (e.g., a patch) etched on a dielectric substrate, which may have a grounded metallic plane at the opposite side. They have been first proposed in the beginning of 1970s. There is a great variety of geometries and ways of excitation. Modern integrated antennas often use multi-layer designs with a feed coupled to the radiator electromagnetically (no galvanic contact).

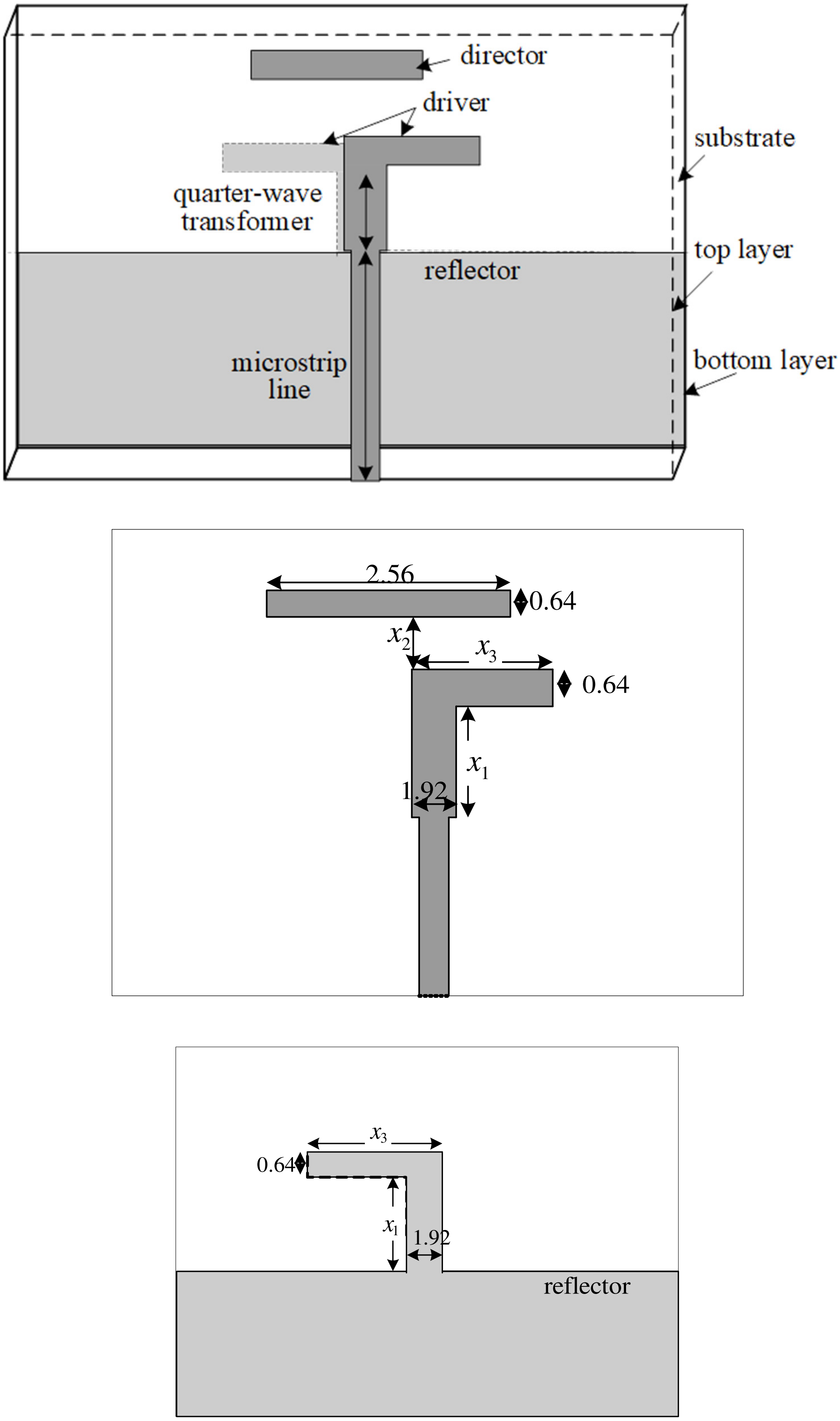
PRINTED PATCH RADIATORS



rectangular patch — circular patch

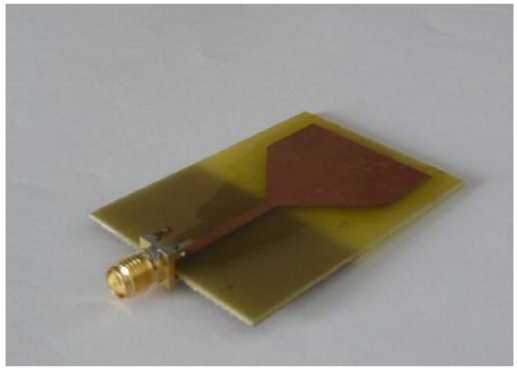


(c)
printed dipole



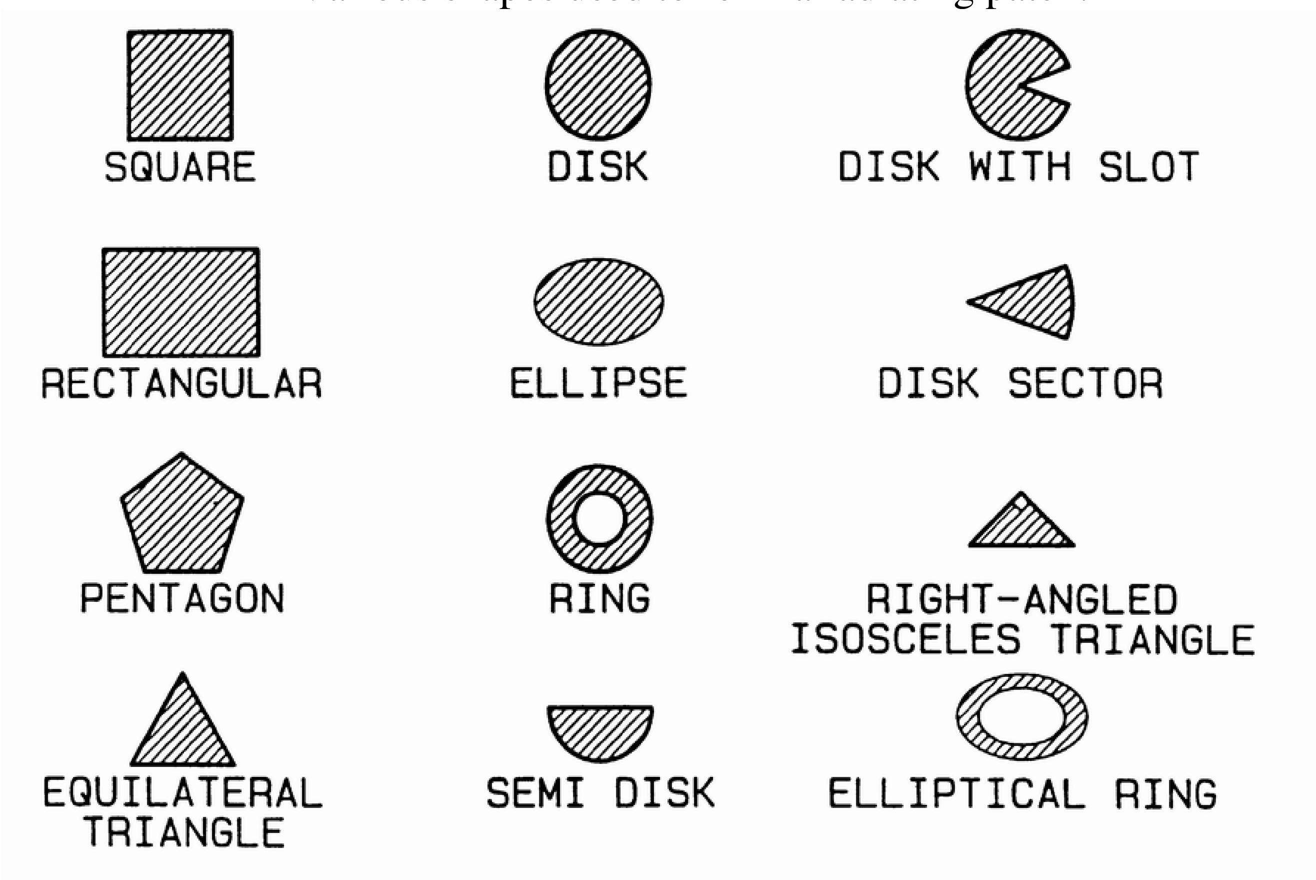
(d)

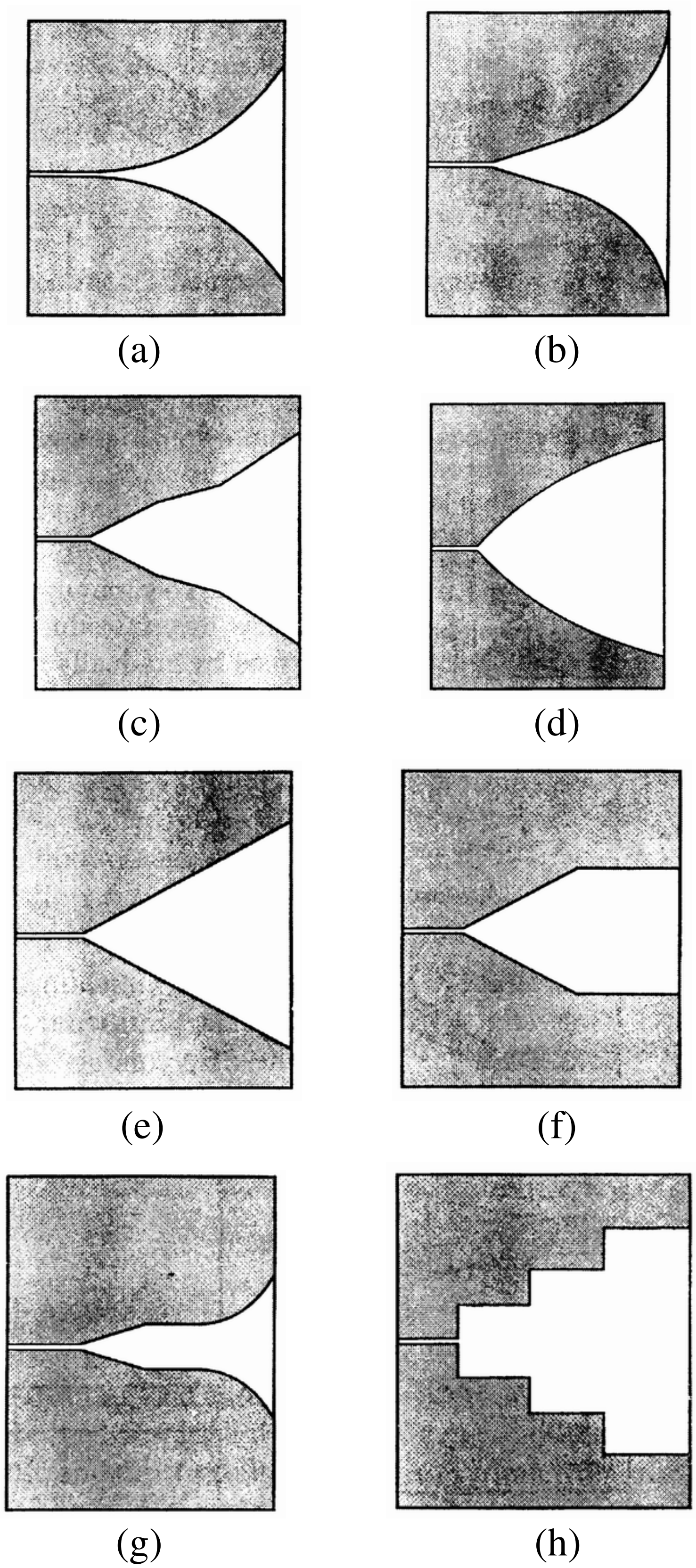
double-layer printed Yagi with microstrip feed



(e)
printed monopole antenna

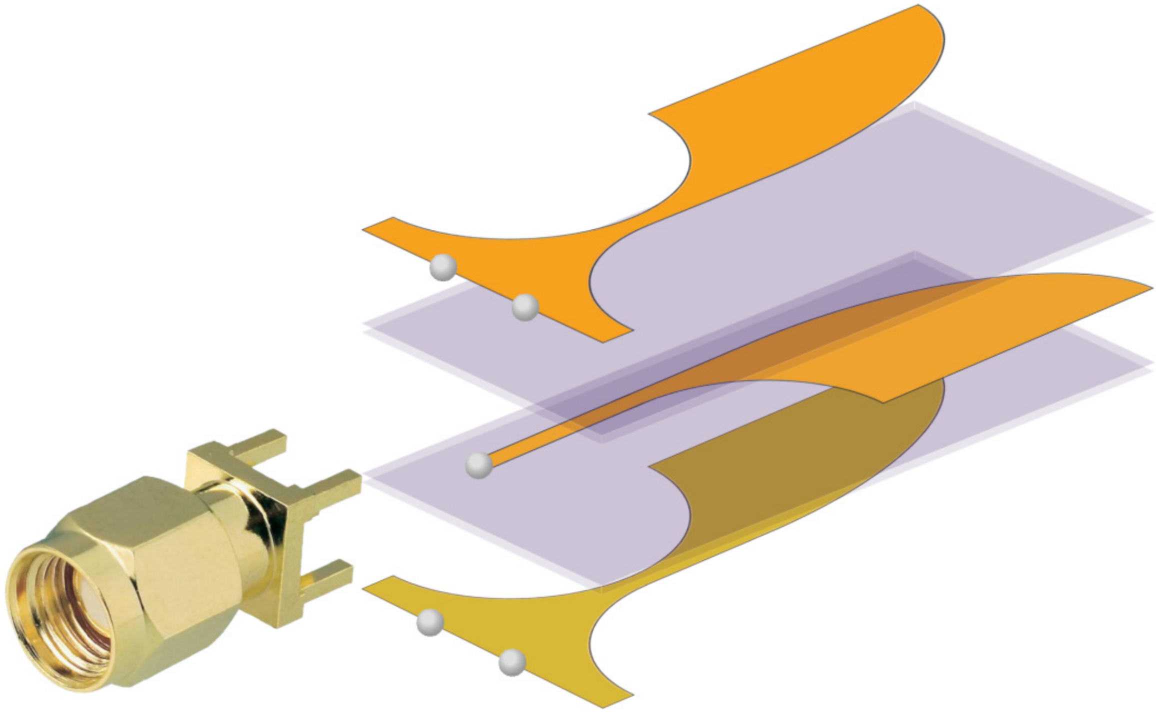
Various shapes used to form a radiating patch:





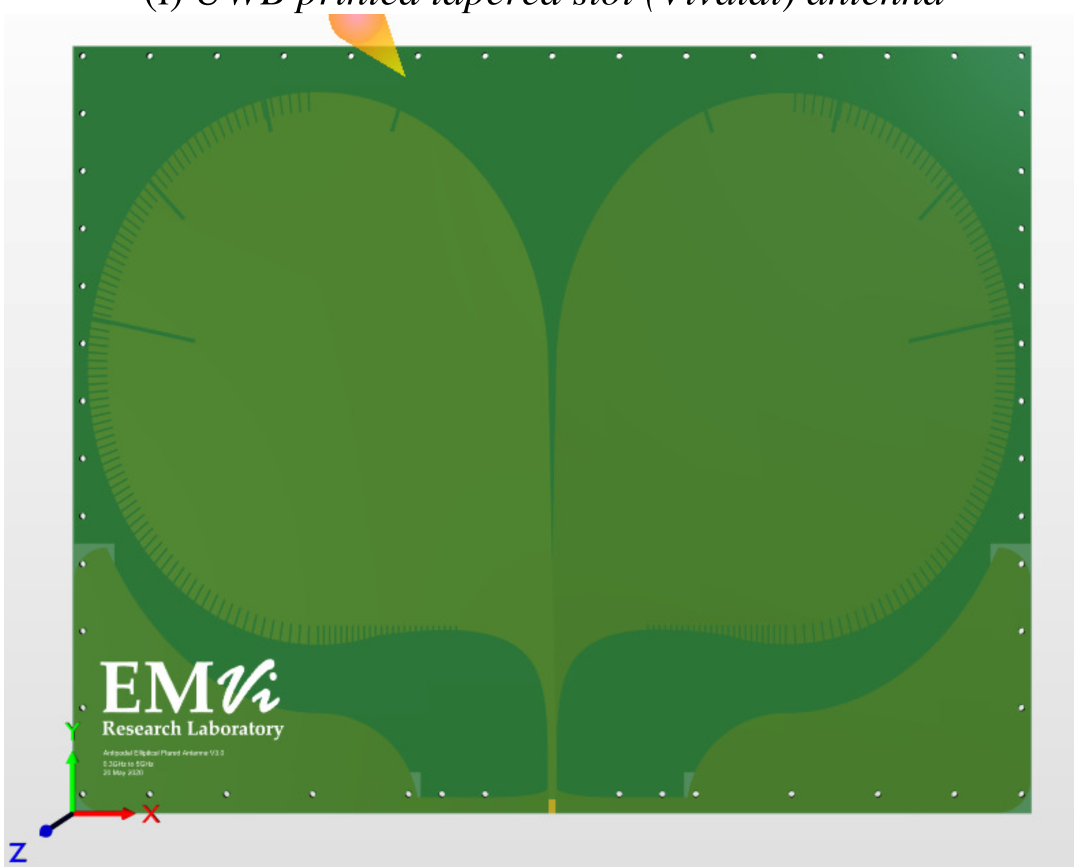
Slot antennas were developed in the 1980s and there is still research on new shapes and types of excitation. They are suited for integration with slot-line circuits, which are usually designed to operate at frequencies above 10 GHz. Popular slot antenna in the microwave range is the Vivaldi slot (see a).

Patch and slot antennas share some common features. They are easy and cheap to fabricate. They are easy to mount; they are light and mechanically robust. They have low cross-polarization radiation. Their directivity is not very high. They have relatively high conducting and dielectric losses. These radiators are widely used in patch/slot arrays, which are esp. convenient for use in spacecraft, satellites, missiles, cars and other mobile applications.



http://www.radartutorial.eu/06.antennas/Tapered%20Slot%20Antenna.en.html

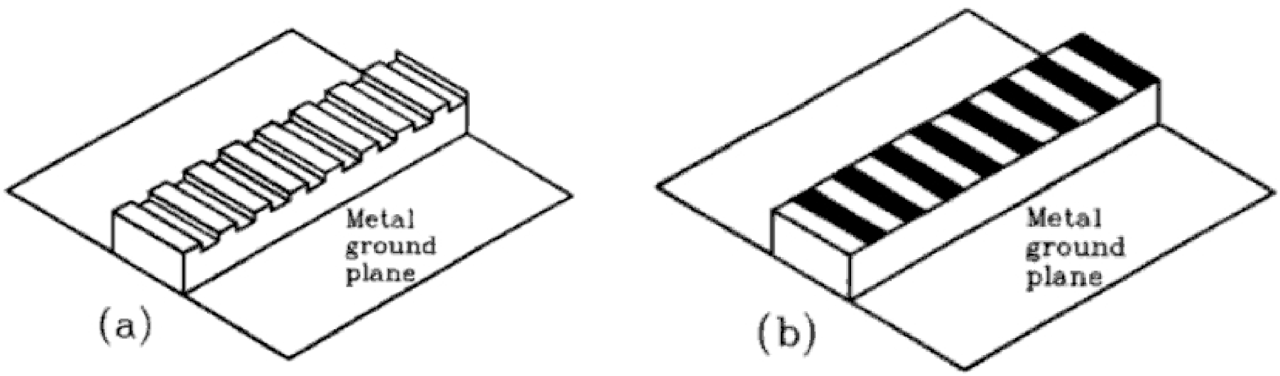
(i) *UWB printed tapered slot (Vivaldi) antenna*



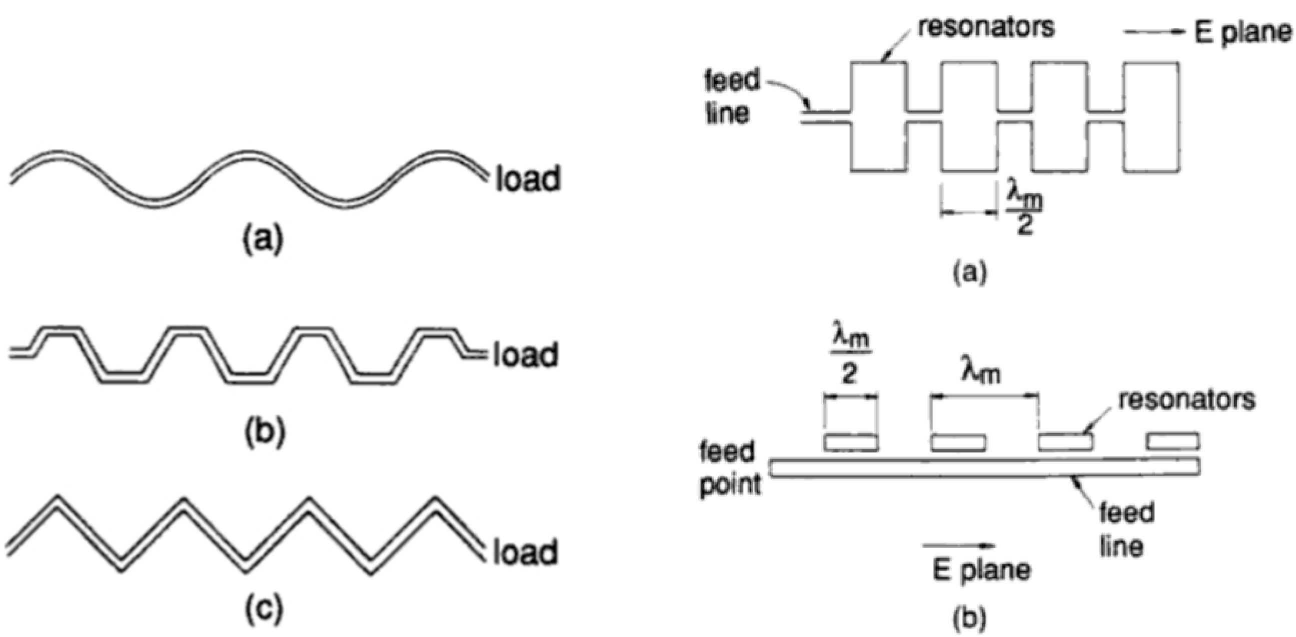
(i) *UWB printed antipodal antenna with suppressed back-radiation*

D. Leaky-wave antennas

These are antennas derived from millimeter-wave (mm-wave) guides, such as dielectric guides, differential microstrip lines, coplanar and slot lines. They are developed for applications at frequencies above 30 GHz, infrared frequencies included. Periodic discontinuities are introduced at the end of the guide leading to substantial radiation leakage (radiation from the dielectric surface). These are traveling-wave antennas.



Dielectric-image guides with gratings



Printed leaky-wave antennas

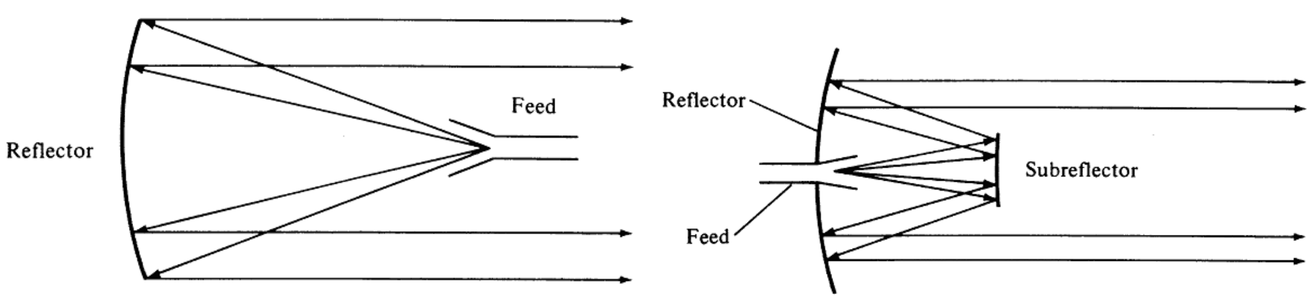
E. <u>Reflector antennas</u>

A reflector of a receiving antenna is used to concentrate the EM energy in a focal point where the feed to the receiver is located. Astronomers have long used mirrors shaped as parabolic surfaces to transforms rays from a source in a focal point into a bundle of parallel rays. A parabolic-cylinder reflector was first used for radio waves by Heinrich Hertz in 1888. Reflectors are usually parabolic but spherical and corner reflectors are also used. Reflector antennas have very high gain and directivity. Typical applications include radio telescopes, satellite communications and radars. These antennas are electrically very large with their size being on the order of hundreds and thousands of wavelengths. They are not easy to fabricate and in their conventional technology they are heavy. Making them mechanically robust to wind, snow and rain may be a challenge.

The largest radio telescopes in the world:

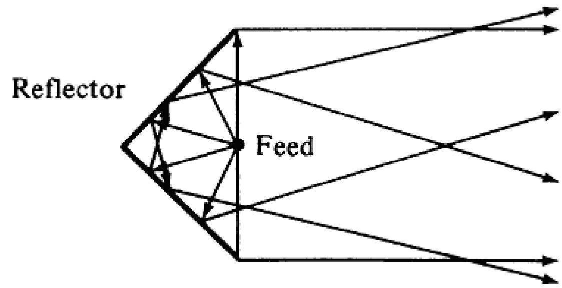
- FAST China (Five-hundred-meter Aperture Spherical radio Telescope), 500-m diameter spherical reflector
- National Astronomy and Ionosphere Center (USA) radio telescope in Arecibo (Puerto Rico), 1000-ft (304.8-m) diameter spherical reflector
- Max Plank Institüt für Radioastronomie radio telescope, Effelsberg (Germany), 100-m-diameter paraboloidal reflector
- The Green Bank Telescope (the National Radio Astronomy Observatory) – paraboloid of aperture 100-m diameter

TYPICAL REFLECTORS



(a) Parabolic reflector with front feed

(b) Parabolic reflector with Cassegrain feed

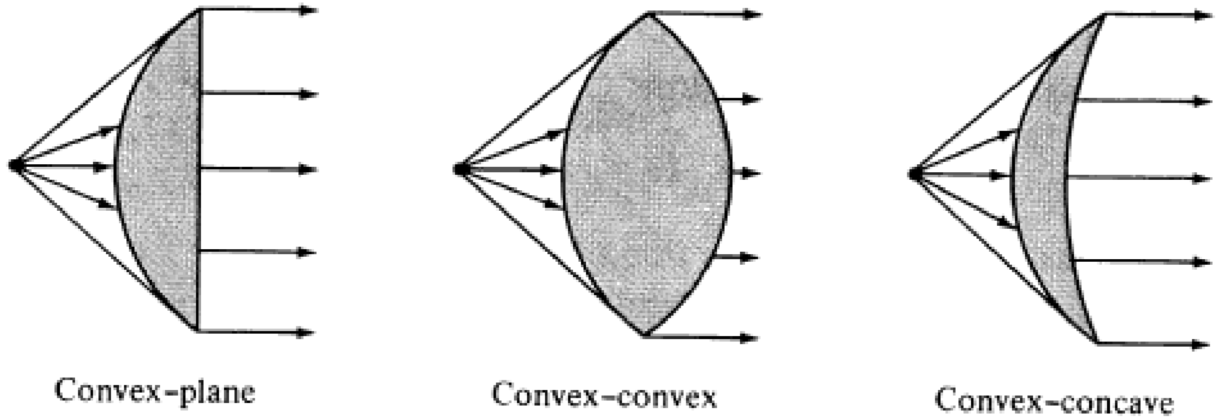


(c) Corner reflector

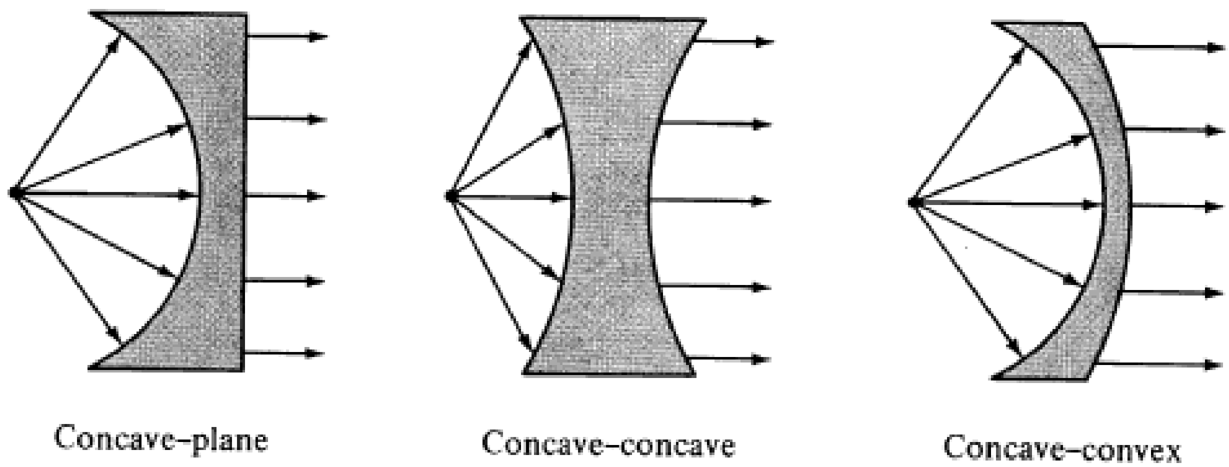
The Radio Telescope of the Arecibo Observatory

F. Lens antennas

Lenses play a similar role to that of reflectors in reflector antennas. They collimate divergent energy into a plane EM wave. Lenses are often preferred to reflectors at higher frequencies (f > 100 GHz). They are classified according to their shape and the material they are made of.



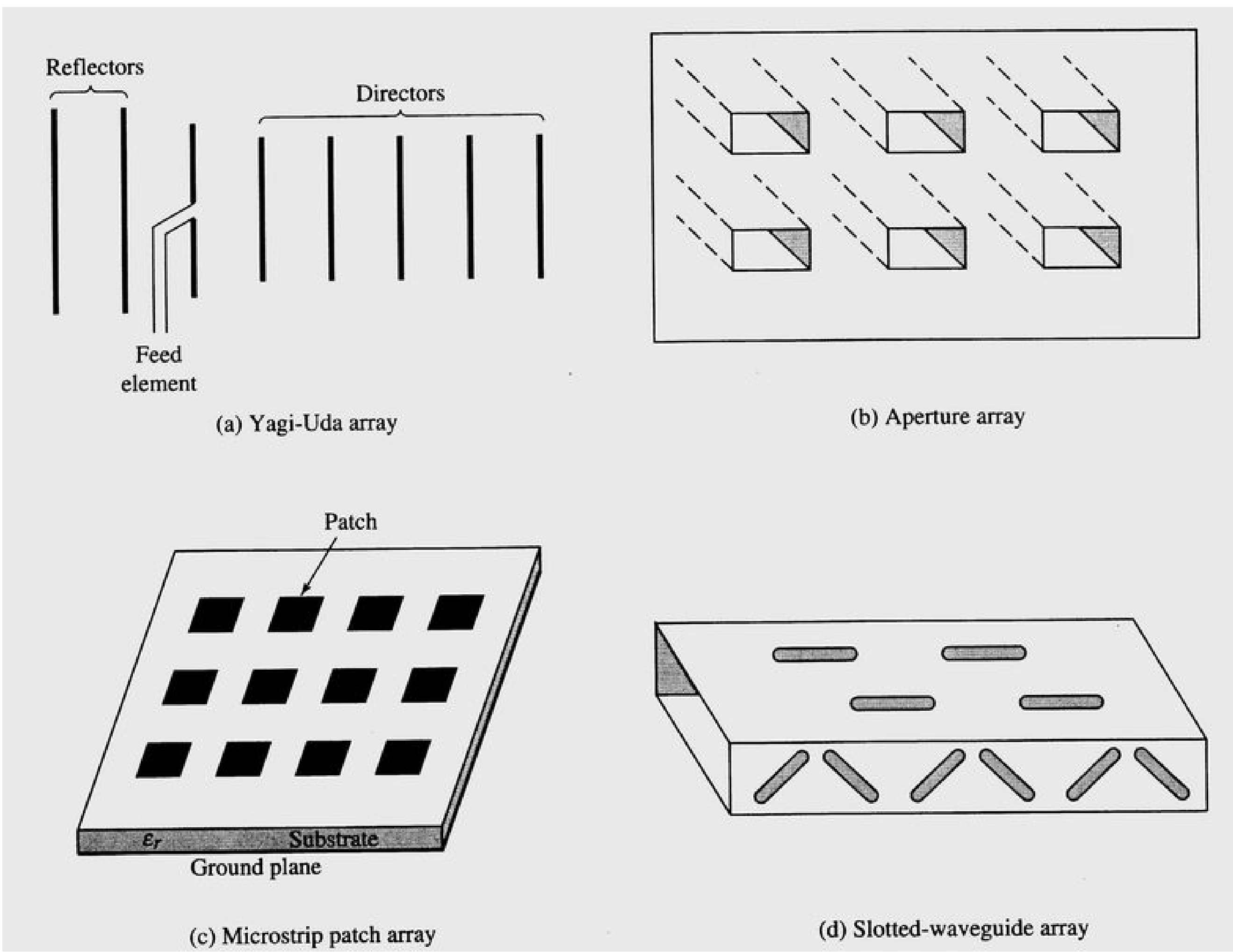
(a) Lens antennas with index of refraction $n > 1$



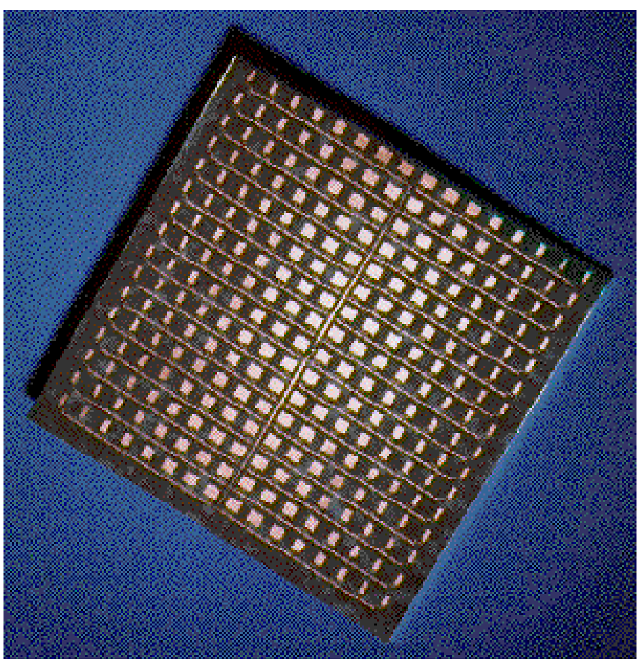
(b) Lens antennas with index of refraction $n < 1$

3.2. Antenna arrays

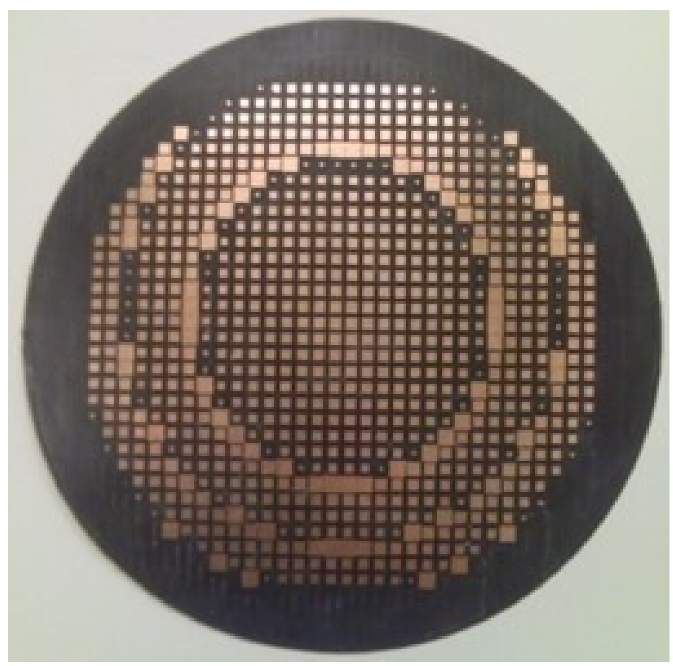
Antenna arrays consist of multiple (usually identical) radiating elements. Arranging the radiating elements in arrays allows for achieving unique radiation characteristics, which cannot be obtained through a single element. The careful choice and control of the phase shift and the amplitude of the signal fed to each element allows for the electronic control of the radiation pattern, i.e., for electronic scanning. Such arrays are called *phased arrays*. The design and the analysis of antenna arrays is a subject of its own and is also related to signal processing and communication theory. Research is ongoing in the subjects of smart antennas, MIMO antennas, tracking antennas, etc. Some commonly met arrays are shown in the figure below.



NRAO/ALMA (Atacama Large Millimeter Array): array of radio telescopes



Array of Microstrip Patches



Reflectarray of Printed Elements

4. Wireless vs. cable communication systems

There are two broad categories of communication systems: those that utilize transmission lines as interconnections (*cable or wire systems*), and those that use EM radiation with an antenna at both the transmitting and the receiving end (*wireless systems*).

In areas of high density population, the cable systems are economically preferable, especially when broadband communication is in place. Even for narrow-band communication, such as voice telephony and low-data-rate digital transmission, it is much simpler and cheaper to build wire networks with twisted-pair cables, when many users are to be interconnected. Such lines introduce very little attenuation at low frequencies, e.g., at about 10 kHz the loss is 2-3 dB/km. At higher frequencies, however, the losses increase and so does the signal dispersion. At 10 MHz, a twisted-pair cable has a typical loss value of 7 dB per 100 meters.

At high-frequency carriers for broadband signals (TV transmission and high-data-rate digital transmission), coaxial cables are commonly used. At 1 GHz, the loss of a typical high-quality coaxial cable is around 2 dB per 100 meters (power decreases about $10^{0.2} \approx 1.6$ times). In the USA, the cable loss is rated in dB per 100 feet, so a good coaxial cable has about 0.6 dB/100ft loss.

The least distortion and losses are offered by the optical-fiber transmission lines, which operate at three different (infrared) wavelengths: 850 nm (≈ 2.3 dB/km), 1300 nm (≈ 0.25 dB/km) and 1550 nm (≈ 0.25 dB/km). Optical fibers are expensive and so is the respective transmitting/receiving equipment.

Transmission lines provide a measure of security and noise-suppression (coaxial, optical-fiber), but they are not the best option in many cases (long-haul transmission, wide spread user network over large areas).

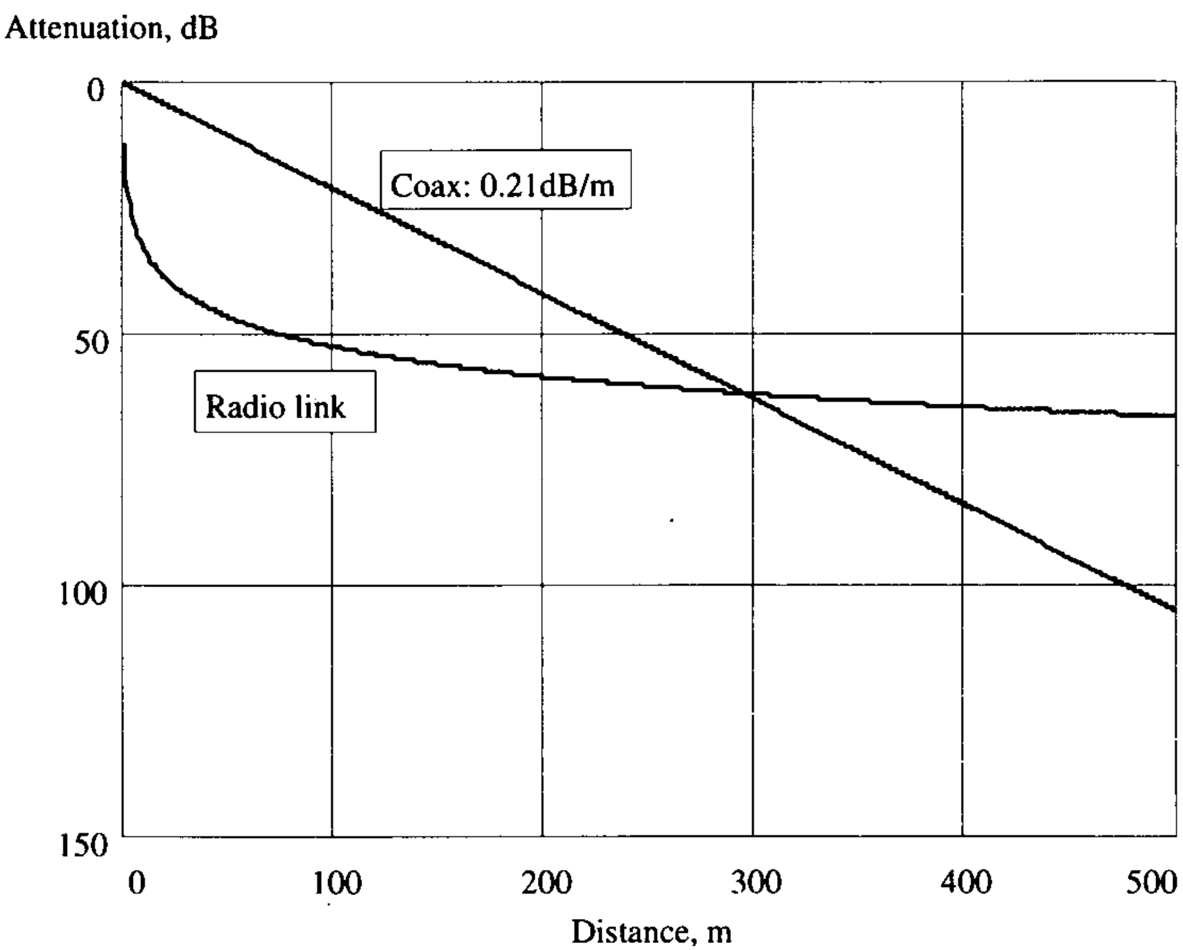
A fundamental feature of all transmission lines is the exponential increase of the lost (dissipated) power. On a dB scale, this means that the power loss is proportional to the transmission-line length. Thus, if the loss is 5 dB/km, then a 20-km line has 100 dB power loss (input power is reduced by a factor of 10^{-10}), a 40-km line will have a 200 dB power (loss factor of 10^{-20}). This is why wireless systems are preferred for long-range communications and in scarcely populated areas.

NOTE: Exponential power loss over a distance d in a transmission line is described by the expression $P(d) = P_0 e^{-2\alpha d}$. Thus, the loss in dB is

$$L_{\text{dB}}(d) = \frac{P_0}{P(d)} = 10\log_{10} e^{2\alpha d} = 20\alpha \log_{10} e \cdot d\,. \quad (1)$$

Here, α is the attenuation constant of the transmission line. From (1) it follows that the power loss in dB is proportional to the distance travelled d (the length of the cable).

In most wireless channels, the radiated power per unit area (power-flow density) decreases as the inverse square of the distance r between the transmitting and the receiving point. Doubling the distance r would decrease the received power by a factor of 4 (or about 6 dB are added to the loss). Thus, if a particular system has a 100 dB loss at $r = 20$ km, doubling the distance will result in 106 dB loss (as compared to 200 dB loss in a cable system). A comparison between the coax-line losses and free-space attenuation at $f = 100$ MHz is given in the figure below.



(Fig. 33 in Siwiak, *Radiowave Propagation and Antennas for Personal Communications*)

Example:

A coaxial cable has a loss $L_c = 0.21$ dB/m. A transmitter sends power $P_{\text{Tx}} = 1$ W through this cable. This same transmitter is used in a wireless link with transmitting (Tx) and receiving (Rx) antennas such that the power received by the Rx antenna P_{Rx}^{w} at a distance of $d_1 = 1$ m from the Tx antenna is the same as the power received at the end of the coaxial cable if this cable's length was $d_1 = 1$ m, i.e., $P_{\text{Rx}}^{\text{w}}(d_1) = P_{\text{Rx}}^{\text{c}}(d_1)$.

a. Find the attenuation constant α of the coaxial cable in Np/m.
b. What is the power $P_{\text{Rx}}^{\text{w}}(d_1) = P_{\text{Rx}}^{\text{c}}(d_1)$ received in the cable and the wireless links if the distance travelled by the signal is $d_1 = 1$ m.
c. What is the power $P_{\text{Rx}}^{\text{c}}(d_2)$ received in the cable link and the power $P_{\text{Rx}}^{\text{w}}(d_2)$ received in the wireless link if $d_2 = 400$ m?

Solution:

a. Attenuation constant of cable in Np/m

$$P_{\text{Rx}}^{\text{c}}(d) = P_{\text{Tx}} e^{-2\alpha d}. \tag{2}$$

When $d = 1$ m,

$$e^{2\alpha} = \frac{P_{\text{Tx}}}{P_{\text{Rx}}^{\text{c}}(1\text{m})} \Rightarrow L_{\text{c[dB/m]}} = 10\log_{10}\left[\frac{P_{\text{Tx}}}{P_{\text{Rx}}^{\text{c}}(1\text{m})}\right] = 20\alpha\log_{10} e \tag{3}$$

$$\Rightarrow \alpha = \frac{L_{\text{c[dB/m]}}}{20\cdot\log_{10} e} \approx \frac{0.21}{20\cdot 0.4342944819} \approx \underline{0.02417714 \text{ Np/m}} \tag{4}$$

b. Received power over distance $d_1 = 1$ m

$$P_{\text{Rx}}^{\text{c}}(d_1 = 1\text{m}) = P_{\text{Tx}} e^{-2\alpha} = 1\cdot e^{-2\cdot 0.02417714} \approx \underline{0.952796 \text{ W}} \tag{5}$$

The same answer can be obtained by using L_c (in dB/m) directly:

$$P_{\text{Rx}}^{\text{c}}(1\text{m}) = P_{\text{Tx}} 10^{-L_c/10} = 10^{-0.021} \approx 0.952796 \text{ W}. \tag{6}$$

This is also the power of the wireless link at a distance of 1 m:

$$P_{\text{Rx}}^{\text{w}}(d_1 = 1\text{m}) = P_{\text{Rx}}^{\text{c}}(d_1) = 0.952796 \text{ W}. \tag{7}$$

c. Received power values over distance $d_2 = 400$ m

There are 3 ways of calculating the Rx power in the cable link.

Method 1:

$$P_{\text{Rx}}^{\text{c}}(d_2 = 400\text{m}) = P_{\text{Tx}} e^{-2\alpha\cdot 400} = e^{-800\cdot 0.02417714} \approx \underline{3.981071\cdot 10^{-9} \text{ W}} \tag{8}$$

Method 2:

$$P_{\text{Rx}}^{\text{c}}(d_2=400\text{m})=P_{\text{Rx}}^{\text{c}}(1\text{m})\cdot e^{-2\alpha\cdot 399}=0.952796\cdot e^{-798\cdot 0.02417714}\approx 3.981071\cdot 10^{-9}\ \text{W} \quad (9)$$

Method 3:

$$L_{\text{c}}^{400}=400\cdot L_{\text{c}}=400\cdot 0.21=84\ \text{dB}\Rightarrow P_{\text{Rx}}^{\text{c}}(400\text{m})=10^{-8.4}\approx 3.981071\cdot 10^{-9}\ \text{W} \quad (10)$$

In dB:

$$P_{\text{Rx}}^{\text{c}}(400\text{m})[\text{dB}]=10\log_{10}\left[P_{\text{Rx}}^{\text{c}}(400\text{m})\right]=10\log_{10}\left(10^{-8.4}\right)\approx -84\ \text{dB}. \quad (11)$$

In the wireless link, the power decays as the inverse square of the distance from the Tx antenna:

$$P_{\text{Rx}}^{\text{w}}(d)=\frac{a}{d^2}, \quad (12)$$

where a is some constant. This constant can be determined if we know the wireless received power at some distance. In our case, this is $d_1=1$ m:

$$P_{\text{Rx}}^{\text{w}}(1\text{m})=P_{\text{Rx}}^{\text{c}}(1\text{m})=\frac{a}{1^2}\Rightarrow a=P_{\text{Rx}}^{\text{c}}(1\text{m})=0.952796\ \text{W}\cdot\text{m}^2. \quad (13)$$

$$\Rightarrow P_{\text{Rx}}^{\text{w}}(400\text{m})=P_{\text{Rx}}^{\text{w}}(1\text{m})\left(\frac{d_1^2}{d_2^2}\right)\approx\frac{0.952796}{400^2}\approx \underline{5.954975\cdot 10^{-6}\ \text{W}}\ (-52.25\ \text{dB}) \quad (14)$$

We see that $R_{\text{Rx}}^{\text{w}}(400\text{m})$ is greater than $R_{\text{Rx}}^{\text{c}}(400\text{m})$ by three orders of magnitude (about 30 dB).

Modern personal mobile communications services

- cordless telephony
- cellular telephony
- mobile voice and data (3G, 4G, now 5G, coming 6G)
- short-range communications: *Bluetooth*; Wi-Fi and WiMAX networks
- personal satellite communications
- global positioning and navigation systems (GPS)
- body-centric communication systems (bio-telemetry and bio-sensing)

Besides, there is a variety of special application of wireless technology in

- radar systems in navigation, guidance, defense, missile, etc.

- imaging radars (synthetic aperture radar (SAR), microwave and millimeter-wave imaging in nondestructive testing and biomedical diagnostics)
- automotive radar
- remote-control vehicles (RCV), unmanned aerial vehicle (UAV, aka *drones*)
- microwave relay links and repeaters
- satellite systems (TV, telephony, military)
- radio astronomy
- biomedical engineering (MRI, microwave imaging, hyperthermia)
- RF identification (RFID)
- animal (migration) tracking, etc.

5. The radio-frequency spectrum

Table 1.1: General designation of frequency bands

Frequency band	EM wavelength	Designation	Services
3-30 kHz	100-10 km	Very Low Frequency (VLF)	Navigation, sonar♣, submarine
30-300 kHz	10-1 km	Low Frequency (LF)	Radio beacons, navigation
300-3000 kHz	1000-100 m	Medium Frequency (MF)	AM broadcast, maritime/ coast-guard radio
3-30 MHz	100-10 m	High Frequency (HF)	Telephone, telegraph, fax; amateur radio, ship-to-coast and ship-to-aircraft communication
30-300 MHz	10-1 m	Very High Frequency (VHF)	TV, FM broadcast, air traffic control, police, taxicab mobile radio
300-3000 MHz	100-10 cm	Ultrahigh Frequency (UHF)	TV, satellite, radiosonde, radar, cellular (GSM, PCS)
3-30 GHz	10-1 cm	Super high Frequency (SHF)	Airborne radar, microwave links, satellite, land mobile communication
30-300 GHz	10-1 mm	Extremely High Frequency (EHF)	Radar, experimental

Table 2.1: Microwave-band designation

Frequency	Old	New
500-1000 MHz	VHF	C
1-2 GHz	L	D
2-3 GHz	S	E
3-4 GHz	S	F
4-6 GHz	C	G
6-8 GHz	C	H
8-10 GHz	X	I
10-12.4 GHz	X	J
12.4-18 GHz	Ku	J
18-20 GHz	K	J
20-26.5 GHz	K	K
26.5-40 GHz	Ka	K

♣ Sonar (an acronym for Sound, Navigation and Ranging) is a system for underwater detection and location of objects by acoustical echo. The first sonars, invented during World War I by British, American and French scientists, were used to locate submarines and icebergs. Sonar is an American term dating from World War II.