Review of Amateur-Built 2.4-GHz Wireless-LAN Directional Wire Antennas

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Abstract

This paper is a review of amateur-built high-directivity wire antennas, for wireless local area network (WLAN), operating at 2.4-GHz frequency range. Those antennas can be deployed for range extension and interference reduction, for example. Covered in this review are a biquad antenna with reflector, Yagi-Uda antenna, and helical antenna. The distinctive feature of these antennas is their ease of construction. The performance of those antennas is highly satisfactory, although they are not the commercial ones. Discussed in this review are their physical structures, directivity (gain), input impedance, and polarization.

Keywords: *WLAN antenna, quad antenna, biquad antenna, Yagi-Uda antenna, helical antenna, helix.*

Introduction

Nowadays, the Internet access is inevitable in daily life. People check their e-mails, and browse the Internet on a daily basis. These activities cannot be accomplished without computer networks. In the past, computers were networked together by means of a wireline technique. Each computer was connected to a hub or switch by using an unshielded twisted pair (UTP) cable (Wikipedia 2009a). The resultant network is called a local area network (LAN). Under some circumstances, the use of cable is not convenient, or even obstructs the access to the network. For example, it is going to be very difficult for people to have their carried notebook computers connected to the network while they are working outdoor.

Thanks to advances in computer technology, today it is possible for computers to connect together wirelessly, which facilitate the use of the Internet dramatically. The wireless computer network is known as wireless LAN (WLAN). The extensive use of WLAN can be understood from the fact that most of the new notebook computers are now equipped with WLAN devices. In order to connect to the network, a WLAN-equipped computer must be within the coverage area of WLAN access point (AP). The most widely used WLAN standard is IEEE 802.11g, which operates at the 2.4-GHz band (Wikipedia 2008). The range of 802.11g WLAN is typically at the order of 100 m (Wikipedia 2008).

One of the most important parts of a WLAN system is the antenna. The main function of an antenna is for signal radiation and reception in the form of electromagnetic waves. Generally, antennas deployed in WLAN devices are low-directivity omnidirectional, which would radiate the WLAN signal (in the form of electromagnetic waves) in all directions equally. Under some circumstances, it is desirable the range between two WLAN devices to be extended, for example, in a rural area where devices are spaced far apart from each other. This task can be achieved by the transmitting antenna radiating most of its available transmitted power to the desired direction instead of radiating the signal in all directions equally. Similarly, the receiving antenna should receive the signal in the desired direction better than in the other directions.

Here comes the necessity of deploying a special-type antenna, which can perform that task, at one end or both. That kind of antenna is usually called a directional antenna. It should be noted that when an antenna transmits the signal in a certain direction stronger than in the other directions, it also receives the signal in that direction better than in the other directions due to its reciprocal property (Balanis 2005). A directional antenna is designed not solely for range extension. It can be utilized for interference reduction (signal quality improvement) due to the fact that a directional antenna transmits and receives in a certain direction better than in the other directions; thus, both transmission and reception of signals in the unwanted directions are minimized. Moreover, a directional antenna can be deployed to limit the coverage area of the AP to a desired area. This is beneficial when users, who want to connect to the network, are concentrated in a certain area. For example, it is useless to radiate the signal to the outside of the building while the users are inside the building.

It is clearly seen that the role of an antenna is important. With directional antennas, network performance can be significantly improved in terms of range, signal quality, and coverage area. There are many companies selling highly-directional (high-directivity) antennas in the market. However, many of those commercial antennas can be constructed in a workshop at home. This leads to the main objective of this paper, which is to review amateur-built high-directivity antennas for 2.4-GHz WLAN. They are widely used by antenna amateurs, who would like to improve the performance of their WLAN networks. The review is to focus on antenna characteristics in terms of antenna directivity, input impedance, and polarization, all of which are briefly explained in the next section. Covered in this review are a biquad antenna (Marshall 2001; Pot 2002; Raminen 2006), Yagi-Uda antenna (ARRL 2007; Yagi 1928; Pozar 1997), and helical antenna (Kraus 1948, 1949, 2003).

Antenna Parameters

When an antenna is considered, the parameters that describe most of the antenna characteristics are directivity, input impedance, and polarization at the operating frequency. Due to the reciprocal property of the antennas, the characteristics of an antenna in its transmitting mode are identical to those in its receiving mode. From this point on, it is assumed that a discussed antenna is in its transmitting mode to ease the explanation of antenna parameters.

Antenna directivity (usually in dB) is the parameter that quantifies how strongly the antenna radiates in a certain direction better than in the other directions. Usually, the term antenna directivity is implied to refer to its maximum value. It should be noted that the antenna directivity (gain) varies with the frequency, and that an antenna is not a lossless device. The latter implies that not all the power fed to an antenna is radiated. The radiation process involves both dielectric loss and conduction loss (Balanis 2006). In order to take into account the said losses, the parameter called gain is used instead. The antenna gain includes the effect of the said losses; therefore, the antenna gain is always less than or equal to the antenna directivity. However, for wire antennas those losses are usually negligible.

A directional antenna does not radiate in all directions equally. In order to deploy the antenna appropriately, it is necessary that the radiation pattern of the considered antenna is known. The antenna radiation pattern is usually given by the plot of the directivity (gain) of the antenna as a function of an observation point. The observation point with respect to the antenna position is usually depicted in terms of an angular position. Since the antenna radiates in all directions, a three-dimensional coordinate system is required.

The most commonly-used coordinate system is the spherical coordinate system as shown in Fig. 1 (Wikipedia 2009b). The antenna is generally placed at the origin. The observation point P in free space is a function of the radial distance r from the origin, the

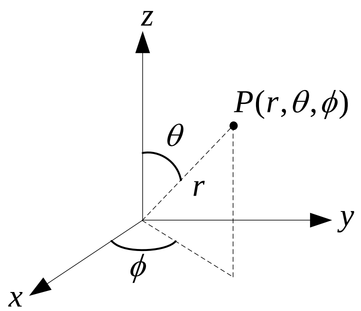


Fig. 1. Spherical coordinate system.

zenith angle θ ($0^\circ \le \theta \le 180^\circ$), and the azimuth angle ϕ ($0^\circ \le \phi \le 360^\circ$).

It should be noted that the radiation pattern is independent of the distance between the observation point and the antenna position provided that the distance is sufficiently long (far-field region) (Balanis 2005). Consequently, the radiation pattern of the considered antenna is a function of only two angular parameters, the zenith angle θ, and the azimuth angle ϕ. The radiation pattern is actually a two-dimensional polar plot of the directivity (gain) as a function of one angular parameter while the other one is fixed to a certain value.

In practice, at least two different radiation patterns are measured or calculated to characterize the antenna radiation. In this review, a considered antenna is placed at the origin and the direction of maximum radiation is along the *x*-axis ($\phi = 0^\circ$). Consequently, two radiation patterns, on the x-z plane and on the x-y plane, are considered. The first one corresponds to the radiation pattern on the elevation plane, in which the zenith angle θ varies from 0° to 180° at $\phi = 0^\circ$ and $\phi = 180^\circ$. The latter one is the radiation pattern on the horizontal (azimuth) plane, in which the azimuth angle ϕ varies from 0° to 360°, and the zenith angle θ is kept fixed at 90°. Radiation patterns are not sufficient to characterize the antenna in terms of its usage. The input impedance and polarization of the antenna must be also considered.

In its transmitting mode, an antenna is connected to a transmitter. The transmitter can be modeled as a voltage source connected in series with its internal impedance. Similarly, the antenna can be modeled as a passive circuit element, which represents the antenna's input impedance. For maximum power transfer, the antenna's input impedance must be equal to the transmitter's internal impedance. This adds another requirement on antenna design. An antenna must be carefully designed such that its input impedance is matched with the transmitter's impedance at the operating frequency. The standard impedance is equal to 50 Ohms at 2.4 GHz. This number comes from the tradeoff between the power-handling capability and the attenuation of the coaxial cable used to connect the antenna (P-N Designs, Inc 2009).

The last antenna parameter, which is needed to be considered, is the antenna polarization. Antenna polarization is just the direction of the electric-field vector of the radiated electromagnetic wave. Generally, the antennas at both ends of the communication systems must be polarization-matched to avoid the penalty called polarization loss factor (PLF) (Balanis 2005). The antenna polarization can be obtained by examining the current directions along the antenna wire.

At this point, all the necessary antenna parameters are briefly explained. The following sections describe the main content of this paper, which is related to the review of amateur-built directional (high directivity) wire antennas for 2.4-GHz WLAN.

Biquad Antenna

The first antenna reviewed in this paper is a biquad antenna. As its name implies, this antenna consists of two quad antennas. Rigorous analysis of the quad antenna was done by Stutzman and Thiele (1998). A quad antenna is just a wire antenna which is constructed by bending a wire so that the wire forms a square as shown in Fig. 2.

When the quad perimeter approaches the wavelength, maximum radiation (directivity) occurs in the directions perpendicular to the quad plane on both sides (Balanis 2005). Thus, the quad perimeter is usually chosen to be roughly equal to the operating wavelength. The quad plane is actually the plane where the considered quad antenna lies.

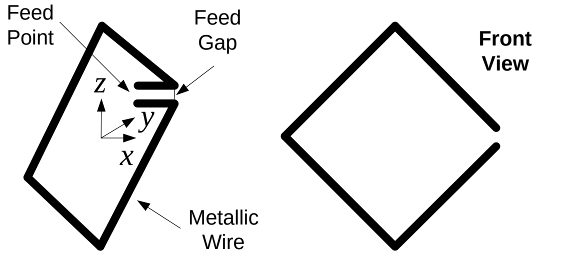


Fig. 2. Corner-fed quad antenna.

According to Fig. 2, that plane is the y-z plane. For 2.4-GHz WLAN, the frequency at the center of the operating frequency band is around 2.442 GHz, which corresponds to an operating wavelength of 123 mm. In general, that number is used as a representative wavelength for 2.4-GHz WLAN signals.

In Fig. 2, one corner of the quad is selected as the feed point (antenna terminal). The quad antenna with this type of feed point is usually called a corner-fed quad antenna. Alternatively, the feed point can be at the middle of a quad side (straight wire section), resulting in a center-fed quad antenna. Note that the feed gap should be made as small as possible.

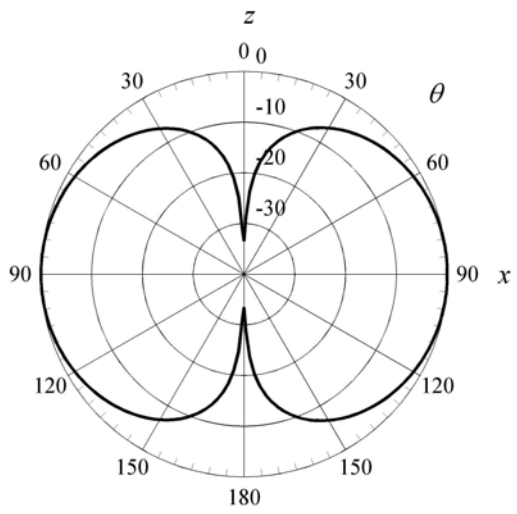
The polar plots of normalized gain (gain normalized by its global maximum) in decibels of the corner-fed quad antenna are shown in Fig. 3. Those plots are obtained by using the widely-used free software called 4NEC2 (4NEC2 2009). This software is suitable for modeling and optimizing wire antennas, and it is very popular among WLAN amateurs. Recall that the quad plane (the plane where the quad antenna lies) is the y-z plane so that the antenna radiates maximally along the x-axis.

It is clearly seen from Figs. 3(a) and 3(b) that the quad antenna radiates symmetrically around its plane, that is, the antenna radiates to its front ($+x$ direction) and its back ($-x$ direction) identically. The radiation pattern is fairly similar to that of the standard half-wavelength dipole. The maximum gain is found to be around 3.5 dB, which is higher than that of the standard half-wavelength dipole.

The input impedance of this antenna consists of resistance and reactance, and it is not close to the standard impedance of 50 Ohms. Thus, the quad antenna alone is not suitable for direct connection with 50-Ohm coaxial cable. According to the current distribution along the quad wire, the polarization of the quad antenna in Fig. 2 is vertical (the z-axis).

To enhance the directivity, two quad antennas can be paralleled together as shown in Fig. 4. This forms a biquad antenna, which is widely used by WLAN amateurs. The biquad antenna is still easy to construct, requiring a piece of wire having the length of approximately twice the wavelength.

The radiation pattern of the biquad antenna is similar to that of the quad antenna shown in Fig. 3. However, paralleling two quad



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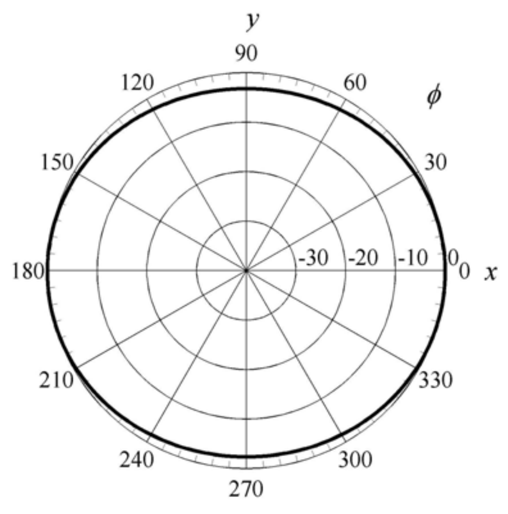


(b)

Fig. 3. Normalized gain of corner-fed quad antenna: (a) Elevation plane; (b) Azimuth plane.

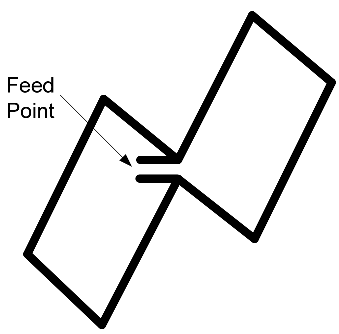
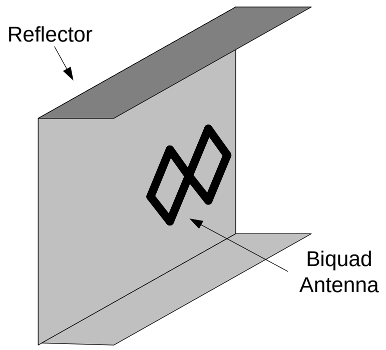


Fig. 4. Biquad antenna. The antenna feed point is at the center of the antenna.

antennas together increases the maximum gain to slightly above 5 dB. Still, the input impedance of the biquad antenna does not match with the standard impedance of 50 Ohms. The directivity can be further improved by deploying a metallic reflector. The biquad antenna is placed above the reflector as shown in Fig. 5. The reflector, in effect, reflects the electromagnetic wave back to the front of the antenna (the *x*-axis); hence, no radiation to the back of the antenna. The purpose of reflector lips in Fig. 5(a) and flared side walls in Fig. 5(b) is to reduce sidelobe radiation, resulting in the increase in the maximum directivity or gain.

The plots of normalized gain in decibels of the biquad antenna with flared reflector depicted in Fig. 5(b) are shown in Fig. 6. The rear reflector width and height both are equal to 120 mm (square rear reflector). The width and height of the flared-side-wall edge are equal to 182 mm (reflector's aperture dimension). This corresponds to the distance between the rear reflector and the flared-side-wall edge of 31 mm. Note that the total length of each quad wire is approximately equal to one wavelength and the total length of a biquad wire is twice the wavelength. For the plots in Fig. 6, the height of the biquad antenna above the rear reflector is 15 mm.



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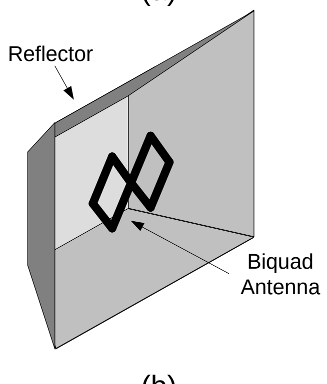
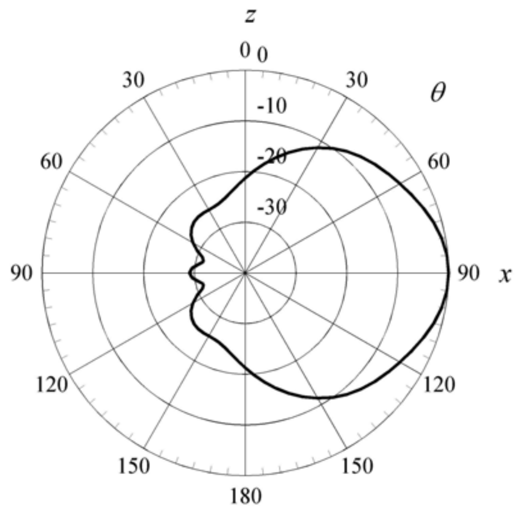


(b)

Fig. 5. Structure of biquad antenna with reflector: (a) Lip reflector; (b) Flared reflector.



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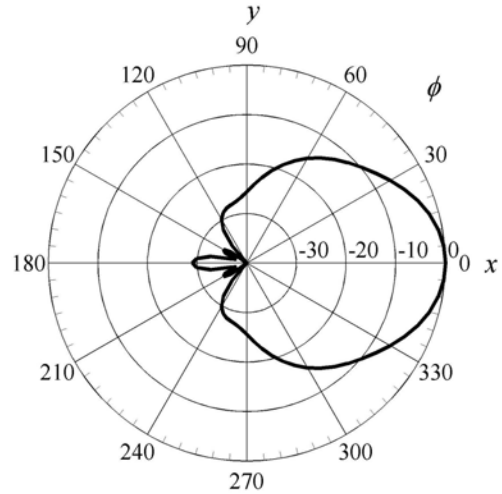


(b)

Fig. 6. Normalized gain of biquad antenna with flared reflector: (a) Elevation plane; (b) Azimuth plane.

It is clearly seen from Fig. 6 that the biquad antenna with reflector radiates strongly to its front, making this antenna very directive. Small radiation to the back is due to a numerical error from the simulation with the 4NEC2 software. Ideally, there should be no radiation to the back of the antenna, since electromagnetic waves cannot propagate through sufficiently-thick metallic sheet. The reflector works effectively to enhance the antenna gain in the forward direction. The gain is found to be slightly below 12 dB at the normal of antenna's front ($\theta = 90^\circ$, and $\phi = 0^\circ$).

Generally, the input impedance of a reflector antenna can be adjusted not only by varying the dimension of the radiating element (in this case, biquad antenna), but also the displacement of the radiating element above the reflector. Although the biquad antenna is a resonant antenna and its impedance is real (no reactance or imaginary part) at a certain frequency only, the antenna's input impedance very close to 50 Ohms across the WLAN frequency range can still be achieved. For the mentioned reflector's physical dimensions, the height above reflector of 15 mm makes the antenna's input impedance very close to 50 Ohms across the WLAN frequency range. Ease of impedance tuning and antenna construction is the main reason as to why this antenna is widely used by WLAN amateurs. The polarization of this antenna is still vertical, similar to that of the radiating element (biquad antenna).

The biquad antenna with reflector can be employed in many applications as mentioned before: range extension, interference rejection, and AP-coverage-area limitation. Furthermore, the biquad antenna with reflector can be utilized as the feed of a parabolic dish, especially an offset parabolic dish (Marshall 2001; Weijand 2009) as shown in Fig. 7. The offset parabolic dish is simply the one used in satellite TV reception; thus, the dish is widely available in the market and inexpensive. The objective of using the parabolic dish is to further enhance the antenna gain. The gain above 20 dB can be readily achieved by deploying the offset parabolic dish with the biquad antenna and reflector as the feed. Consequently, the range between two WLAN devices could be extended dramatically.

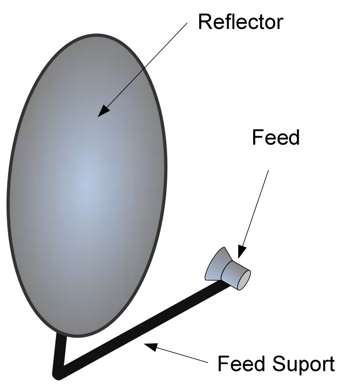


Fig. 7. Offset parabolic-dish antenna.

Yagi-Uda Antenna

The Yagi-Uda antenna is one of the most widely used antennas around the world. The structure of this antenna is shown in Fig. 8. This antenna was developed by Shintaro Uda and Hidetsugu Yagi of the Tohoku Imperial University in 1920s (Pozar 1997). Due to its simple robust structure, low wind resistance, and ease of construction, this antenna has found its extensive uses in many applications, especially for outdoor uses. They range from TV signal reception, amateur radio transmission, radar, etc. Most of the houses around the world have this antenna on their rooftops for TV reception. Moreover, the Yagi-Uda antenna can also be used for WLAN applications.

The Yagi-Uda antenna, shown in Fig. 8, consists of an array of parallel dipoles placed at different positions along the antenna boom. The farthest element, which is usually the longest one, is called the reflector. The element next to the reflector is a dipole with the feed point. This element is called radiator. The other elements, which are typically shorter than the reflector, are called directors. Normally, spacing between adjacent elements is between 0.2 and 0.3 of the wavelength (Pozar 1997).

The Yagi-Uda antenna is actually an array antenna. The feature of this array is that only one array element is driven, which facilitates the antenna construction. The

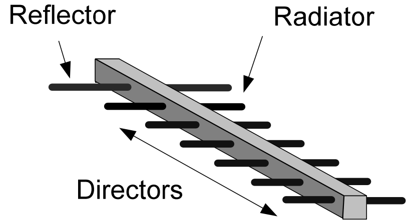


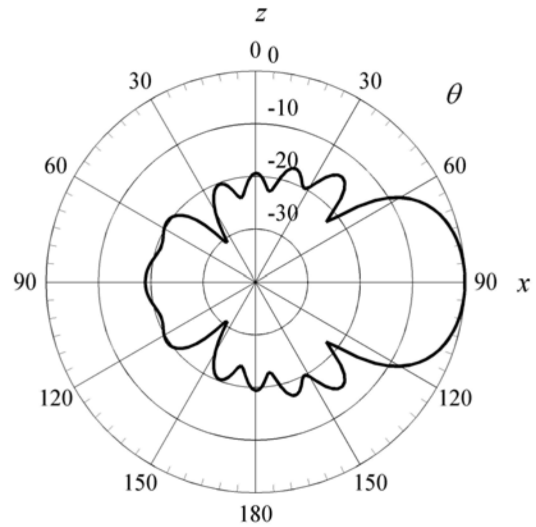
Fig. 8. Yagi-Uda antenna.

nondriven reflector and director elements are excited by mutual coupling between themselves and the radiator. The direction of maximum radiation (maximum directivity or gain) is along the directors (the *x*-axis). Generally, the antenna has only one reflector. Additional reflectors slightly increase the antenna gain, because the radiation is mainly toward the director position.

On the other hand, adding more director elements increases the antenna gain. It should be noted, however, that the increase in the gain reaches its saturation after 10–15 director elements (Pozar 1997). Fig. 9 shows the simulated normalized radiation patterns of 12-element Yagi-Uda antenna (1 reflector, 1 radiator, and 10 directors). The antenna array elements lie on the x-y plane with the direction of radiators along the *x*-axis ($\theta = 90^\circ$, and $\phi = 0^\circ$), which is the direction of maximum gain. The antenna gain is very close to 14 dB at that direction. Although there is the backward radiation (the direction of reflector), the level of radiation is small, compared with the forward radiation (direction of directors). The difference is around 20 dB, which can be seen from Fig. 9.

The input impedance and gain of the Yagi-Uda antenna across the operating frequency range can be optimized by adjusting element spacings, element length, and the number of elements (Thiele 1969; Cheng and Chen 1973 and 1975; Balanis 2005). Similarly to the biquad antenna reviewed in the previous section, the Yagi-Uda antenna is a resonant antenna. Thus, it has narrow operating bandwidth in terms of the input impedance. Nonetheless, the antenna's input impedance can be made very close to 50 Ohms across the 2.4-GHz WLAN frequency range by fine-tuning the mentioned parameters. The polarization of the Yagi-Uda antenna is determined from that of the radiator. Since the radiator is a dipole antenna, which lies along the y axis, the polarization is horizontal in the direction of maximum radiation for the Yagi-Uda antenna shown in Fig. 8.

Both the biquad antenna with a reflector and the Yagi-Uda antenna have linear polarization. Linear polarization means that the radiated-electric-field vector at a point in space is always directed along a line as a function of time (Balanis 2005). Actually, the radiated-electric-field vector at a point in space can be traced as a circle as a function of time. That is, the radiated-electric-field vector can rotate like a clock arm in either clockwise or counter-clockwise direction, observed behind the direction of radiated electromagnetic wave. That kind of polarization is called circular polarization. There are many kinds of antennas that exhibit circular polarization. One is the helical antenna, which is discussed in the next section.



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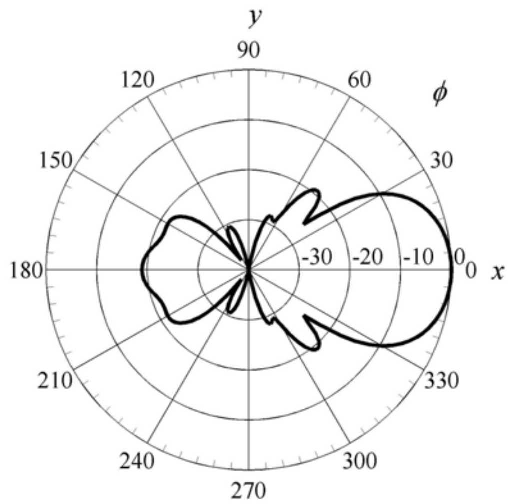


(b)

Fig. 9. Normalized gain of 12-element Yagi-Uda antenna: (a) Elevation plane; (b) Azimuth plane.

Helical Antenna

The axial-mode helical antenna is among the most widely used circularly-polarized high-directivity antennas. The physical structure of a helical antenna is shown in Fig. 10. The antenna is merely a helical coil with a ground plane (reflector). The purpose of the ground plane is to reduce the backward radiation, hence, increasing the forward radiation (gain). At the feed point, one terminal is connected to the end of the helix wire and the other terminal is connected to the ground plane. For coaxial-cable connection, the outer conductor (shield) of the coaxial cable is usually connected to the ground plane while the inner connector is terminated to the end of the helix wire. The geometry of a helical antenna is described by the helix circumference, pitch angle, and the total number of turns. The pitch angle α is related to the spacing between turns S and helix circumference C by $\tan(\alpha) = S / C$.

Generally, a helical antenna has two operating modes: normal mode and axial mode, depending on its circumference compared with the operating wavelength (Kraus 2003). The operating mode actually depicts the direction of maximum radiation (maximum gain). When the helix circumference is very small compared with the operating wavelength, the helix operates in its normal mode. In this mode, the direction of maximum radiation is normal (perpendicular) to the helix axis. The normal-mode helix has narrow operating bandwidth and radiation efficiency; therefore, this mode is rarely used in practice.

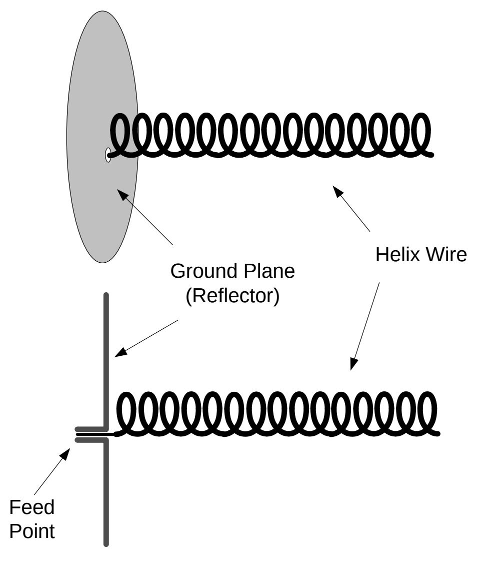


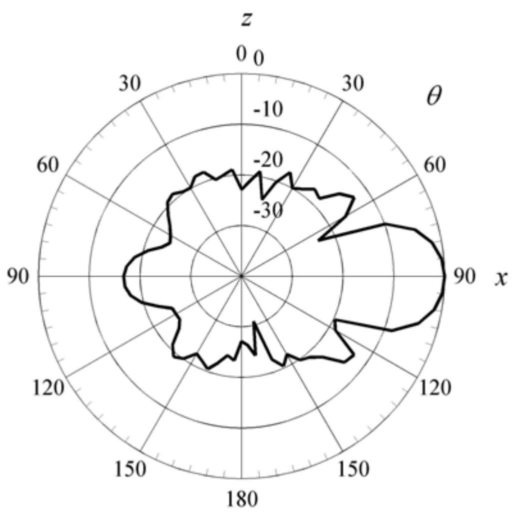
Fig. 10. Helical antenna with ground plane (reflector).

On the other hand, the axial-mode helix radiates maximally along the helix axis. In order to operate in the axial mode, the helix circumference normalized by the operating wavelength must be between 0.8 and 1.2 and the optimum pitch angle is $12^\circ \le \alpha \le 14^\circ$ (Kraus 2003). The helical antenna is usually utilized in this mode, since it has wide operating frequency range in terms of input impedance and radiation pattern. The impedance and radiation pattern of the helix do not change significantly across the operating frequency range. Moreover, the impedance is nearly resistive (no reactance) in the axial mode. It should be noted that when the helix circumference is beyond the mentioned range, the radiation pattern consists of a large number of lobes. Thus, large-circumference helix is of little interest in practice.

Owing to its simple structure and wide operating bandwidth, an axial-mode helical antenna is widely used in many applications requiring circular polarization and high directivity, such as space communications (NASA 2001), satellite communications (Coatl and Flores-Mena 2005), global positioning system (GPS) (Wikipedia 2009c), WLAN (Besten 2008; Hecker 2003), etc.

In operation, the gain of the axial-mode helical antenna increases with the total number of helix turns. In this way, it is relatively easy to realize a high-gain axial-mode helical antenna. Plotted in Fig. 11 are the simulated normalized radiation patterns of a helical antenna in the elevation plane and the azimuth plane. The helix axis coincides with the *x*-axis in the plot (i.e., the helix wire is wounded toward the *x*-axis and the ground plane lies on the *y*-*z* plane.).

The antenna parameters used in the plots in Fig. 11 are: normalized circumference of 1.08, pitch angle of 12.4°, and total number of 16 turns. It is clearly seen that the direction of maximum gain is along the *x*-axis (helix axis). Radiation in other directions is small compared with the direction of maximum radiation. The



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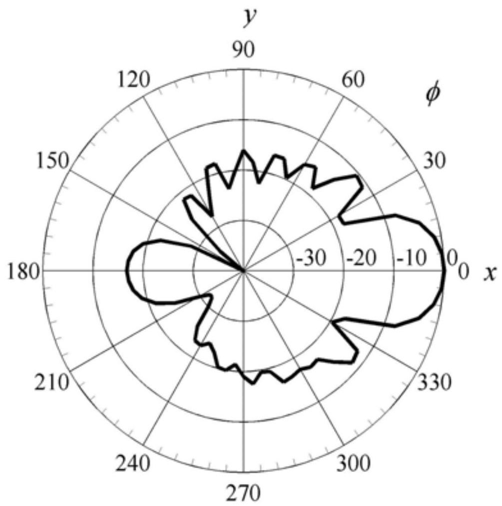

(b)

Fig. 11. Normalized gain of 16-turn helical antenna: (a) Elevation plane. (b) Azimuth plane.

maximum gain is very close to 18 dB along the *x*-axis. Radiation patterns on both planes are similar, since the helix is rotationally symmetrical around its axis (the *x*-axis). Small asymmetry of the pattern shown in Fig. 11 is due to the feed point being at the helix circle and the numerical error from the simulation.

In order to utilize an antenna effectively, not only it radiation pattern but also its input impedance must be considered. Even though the impedance of the axial-mode helical antenna is nearly resistive, its value is well above 50 Ohms. Thus, the impedance mismatch cannot be ignored. Several techniques have been proposed to lessen that impedance mismatch. Tapering the last several helix turns has been shown to help reduce the impedance mismatch over a wide frequency band (Wong and King 1979). Gradually tapering helix windings at both ends, and deploying a cone reflector could alter the input impedance as desired (Angelakos and Kajfez 1967).

Alternative approach to solve the impedance mismatch is to deploy a tapered transmission line of a short length between the feed point of the helical antenna and the main coaxial cable (Bart 2003; Manthur and Sinha 1988; Tsandoulas 1967). Similarly, gradually flattening the section of a helical wire near the feed point also results in a smooth transition to 50-Ohm standard-coaxial-cable impedance at the feed point (Kraus 1977 and 2003).

Another approach is to replace a section of the helix wire near the feed point by a thin triangular copper strip (Besten 2008; Hecker 2008). This approach is suitable when the helix wire is wound around a circular tube. Winding the helix wire around a circular tube not only strengthens the antenna structure, but also facilitates the antenna construction. The wide allowable strip length makes this impedance-matching approach attractive (Wongpaibool 2008a, 2008b and 2008c). Moreover, the wide-bandwidth feature of the helical antenna is still preserved. Due to its high gain, the helical antenna can help extend the range between two WLAN devices. Hecker (2003) and others have successfully deployed the helical antennas to extend the range of WLAN links to several kilometers.

Conclusion

In this paper, a biquad antenna with reflector, Yagi-Uda antenna and helical antenna for 2.4-GHz WLAN are reviewed. Each antenna has its own distinguishing feature. A biquad antenna with reflector is simple to build. It can be deployed as stand-alone antenna or as a feed for a parabolic reflector, which would further enhance the antenna gain. Another antenna, which is extensively used around the world, is the so-called Yagi-Uda antenna. The gain of this antenna increases with the increase in the number of directors; thus, high gain can be accomplished with ease. Impedance matching for both antennas is achieved by adjusting antenna's physical dimensions. The polarization of both antennas is linear.

On the other hand, an axial-mode helical antenna exhibits circular polarization. The gain of a helical antenna generally increases with the number of helix turns. Impedance matching can be accomplished by several techniques. The distinctive advantage of the helical antenna is its wide operating bandwidth, compared with the biquad antenna and the Yagi-Uda antenna.

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