Printed Slot and Wire Antennas: A Review

Techniques for enhancing the bandwidth of printed slot antennas fed by transmission lines, methods of generating circularly polarized waves, and radiation characteristics of various wire antennas are discussed.

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ABSTRACT | The first part of this paper focuses on printed slot antennas. Starting with discussions of a narrow modified slot and a wide slot fed by a microstrip line, we proceed to a topic of generation of a circularly polarized beam. In addition, a rectangular slot antenna fed by a coplanar waveguide is described. The modification of a rectangular slot into an elliptical slot for enhancing the bandwidth is also presented. The second part of this paper covers wire antennas, first presenting the theoretical treatment and then the radiation characteristics of various configurations. It is described that a multiloop antenna exhibits multiband characteristics; a spiral antenna has wideband characteristics with the help of resistive material; and a helical element, having only the C region, radiates a circularly polarized wave. An inverted F-antenna (IFA) backed by an electromagnetic band gap (EBG) reflector and a composite helical and spiral (CHES) antenna are then presented, both radiating a tilted beam. Next, a curl antenna array that has an unrivaled aperture efficiency of more than 90% is introduced.

KEYWORDS | Circularly and linearly polarized waves; printed slot antennas; wideband and multiband operation; wire antennas

I. INTRODUCTION

Low-profile antennas are required for communication systems where the antenna installation space is limited [1], [2]. Bandwidth enhancement is also a requirement, particularly for ultrawideband (UWB) applications. Printed slot and wire antennas meet these requirements. In this paper, recent advances in these antennas are reviewed. Although there has been done much work in this field, due to limited space we mainly refer to the frequently cited papers. Note that an enhanced bandwidth reduces insensitivity to configuration parameters, and therefore increases fabrication tolerances in mass production.

Section II-A describes printed slot antennas fed by a microstrip line. First, a narrow slot antenna is presented and then its configuration is modified to meet reduced size requirements. The frequency response of the return loss characteristics is mentioned. A wide-slot antenna is also discussed, in which a fork-like tuning stub or a simple rotated slot is used to enhance the operating bandwidth. Next, the generation of a circularly polarized (CP) wave is summarized using two different structures. The axial ratios of the dual-spiral slot and printed ring-slot antennas are discussed. Section II-B focuses on coplanar waveguide (CPW) fed slot antennas. A key technique for widening bandwidth is to use an appropriately designed tuning stub. For a square slot antenna, a widened tuning stub contributes to wideband operation, while for a rectangular slot antenna, a T-shaped exciting stub achieves wideband operation. Further study shows that modifying the rectangular slot to an elliptical slot also serves to enhance the bandwidth.

Section III-A presents numerical analysis methods for wire antennas, where the wire is arbitrarily shaped and is located 1) in free space, 2) on a dielectric substrate backed by a conducting ground plane, or 3) on a semi-infinite dielectric material. The arbitrarily shaped wire antenna for each of these three cases is formulated using an electric field integral equation, where the current on the wire is treated as an unknown function. Section III-B describes the antenna characteristics for representative low-profile wire antennas, including loop, spiral, helical, inverted F, and composite helical and spiral (CHES) antennas. Techniques for realizing multiband operation and wideband operation are discussed. In addition,
realization of CP radiation, a tilted beam, and a steerable beam are discussed. Section III-C refers to low-profile wire array antennas, including curl, helical, and grid arrays. Section IV provides brief conclusions.

II. PRINTED SLOT ANTENNAS

A. Slot Antennas Fed by a Microstrip Line

1) Printed Narrow-Slot Antenna: Antenna miniaturization (achieving a small antenna height) for mobile handsets and other wireless applications is an important issue [3]. For such applications, a slot antenna is of major interest, because of its simple structure. A basic structure of the slot antenna consists of a narrow straight slot fed electromagnetically by a microstrip transmission line. The configuration of the straight slot can be modified to meet reduced size requirements. An extensive study of this type of antenna has been done by Shafai et al. [4], [5].

The geometry of an L-slot antenna, with straight, inclined, and bent feed lines, is shown in Fig. 1(a)–(c). The L-slot is positioned at the center of the edge of a narrow ground plane and is fed by a 50-Ω microstrip line (height 0.81 mm). The slot comprises one vertical slot of length $L_1$ and one horizontal slot of length $L_2$, with their ends connected. The overall slot length is kept close to one-quarter wavelength. Compared to the straight slot case, the L-slot is occupying only 23% of the ground plane length ($G_L$), leaving more space for electronic circuitry. The width of the microstrip feed line is chosen such that its characteristic impedance is 50-Ω on the feed line substrate. The feed line is excited by a 50-Ω probe, as shown in Fig. 1. The optimized antenna parameters are included in the caption of Fig. 2. The simulated return loss data for the L-slot antenna on a lossy FR-4 substrate, with the straight, inclined, and bent feed lines, are shown in Fig. 2(a). The impedance bandwidths are 82.1% (2.24–5.36 GHz), 75.7% (2.48–5.5 GHz), and 67.2% (2.47–4.97 GHz), respectively, for a 10-dB return loss criterion.

To help understand the phenomenon behind this wideband impedance performance, a Smith chart of the input impedance is given in Fig. 2(b). It shows three loops, corresponding to four nulls present on its return loss plot in Fig. 2(a). Thus, a monopole L-slot shows four dominant resonances, as compared to two for a straight slot. It appears, therefore, that the two orthogonal arms of the slot act as separate and tightly coupled resonators, and their mutual coupling displaces their resonances toward lower and higher end frequencies, as shown in Fig. 2(a). This phenomenon enlarges the bandwidth significantly.

Note that the horizontal arm length can be further increased by converting the L-slot into an inverted T-slot. Details on this topic can be found in [4].

2) Printed Wide-Slot Antenna: Another way to achieve wideband characteristics is to combine a wide slot with a tuning stub [6], [7]. Sze and Wong [8] have investigated an example of this structure.

The configuration of this type of antenna is shown in Fig. 3(a). The wide slot is fed by a 50-Ω microstrip line with a fork-like tuning stub, which is printed on the opposite side of the microwave substrate (0.8-mm thickness) and placed symmetrically with respect to the centerline of the wide slot. By selecting proper dimensions for the fork-like tuning stub, a good impedance match can be obtained for the printed wide-slot antenna over a significantly enhanced bandwidth.

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**Fig. 1.** L-slot antenna, fed using three different shape feed lines: (a) straight, (b) inclined, and (c) bent. (From [4].)
Measured return loss results from several design examples (denoted as antennas 1–3) are shown in Fig. 3(b). A conventional antenna with a simple straight tuning stub (denoted as the “reference antenna”) is also illustrated for comparison. It is seen that antenna 2 has an impedance bandwidth of 1091 MHz for a VSWR (voltage standing wave ratio) \( = 1.5 \) criterion, which is nearly ten times that of the reference antenna (115 MHz). Antennas 1 and 3 also have bandwidths that are larger than the reference antenna. This bandwidth enhancement is obtained mainly through the improved coupling between the microstrip feed line and the wide slot provided by the fork-like tuning stub.

Jan and Su introduced a different approach to enhancing the bandwidth [9]. They proposed a printed wide-slot antenna with a slot rotated by an angle \( \alpha \), as shown in Fig. 4(a). The printed wide slot is chosen to be a square, in order to excite two modes with close resonant frequencies. The ground plane is also chosen to be square. Simulated results show that square slot antennas with various rotation angles need different tuning-stub lengths [\( L \) in Fig. 4(a)] to obtain impedance matching.

The measured and simulated return loss results are shown in Fig. 4(b). It is found that the widest bandwidth can be obtained when the rotation angle is nearly 45°. This is due to the fact that resonant modes in the vicinity of the fundamental mode can be excited by the rotated square wide slot. The impedance curve can have different loops on the Smith chart depending on the rotation angle of the square slot.

3) Printed Slot Antennas Generating a CP Wave: Up to now, we have described antennas that radiate a linearly polarized wave. However, applications, for instance, to satellite communications, require generation of a CP wave, since we do not need to pay attention to the direction of polarization, as long as the rotational sense of the CP is the same. There are several methods for obtaining a CP wave in slot antennas.
Hirose and Nakano [10] have proposed a dual-spiral slot antenna fed by a triplate transmission line (TTL). Generation of a CP wave can be expected by analogy from its wire counterpart. The use of the TTL contributes to generating a unidirectional beam. The configuration is shown in Fig. 5(a), where the thickness of the TTL is 4 mm. To obtain a good axial ratio, a traveling-wave magnetic current is necessary, since it provides a phase rotation of $2\pi/\lambda$ rad along an effective one-wavelength circumference of the spiral. This can be achieved by properly choosing the length of the spiral arm. Fig. 5(b) shows the return loss under CP radiation; the bandwidth for a 14-dB return loss (VSWR = 1.5) criterion is 4.2%.

Wong et al. have presented a printed ring-slot antenna that introduces asymmetry in the slot structure [11], as shown in Fig. 6(a). A meandered slot section is used to perturb the symmetry of the ring-slot antenna, splitting the fundamental resonant mode into two orthogonal degenerate resonant modes for CP radiation. The optimal value of the meander length $l_2$ in this study is obtained through numerous experiments, and is found to be approximately 40% of $L_2$ (the square ring-slot’s inner linear dimension). The measured axial ratio is shown in Fig. 6(b). This design can also be applied to an annular-ring-slot antenna. Details on this antenna can be found in [11].

### B. Slot Antennas Fed by a CPW

The planar CPW system is an attractive feed system, due to its ease of integration with radio-frequency/microwave circuitry, thereby lowering the manufacturing cost [12], [13]. Some attempts to broaden the bandwidth have been performed using the CPW system [14]–[18].

Chen [14] has introduced a CPW-fed square slot antenna with a widened tuning stub. The impedance bandwidth is mainly determined by the width and length of the tuning stub. The maximum impedance bandwidth reaches 1320 MHz (1560–2880 MHz; approximately 60%).

A similar approach has been adopted by Lin and Hung [15]. They developed a compact UWB aperture antenna using a T-shaped feed stub. The configuration of this antenna is shown in Fig. 7(a). The measured and simulated return loss of the optimized configuration is shown in Fig. 7(b). The input impedance is well matched, so that the 10-dB return loss bandwidth covers the entire UWB.
band (3.1–10.6 GHz). The difference in the bandwidth between the two models in [14] and [15] mainly results from the optimization of the aperture shape.

A different approach was developed by Chiou et al. [16]. They introduced four metallic strips, which protrude from the four corners of a square slot toward the slot center, as shown in Fig. 8(a). The measured return loss is given in Fig. 8(b). The presence of the loading strips causes a new resonant mode to be excited. By selecting an appropriate length for the loading strips, this new resonant mode can be shifted close to the antenna’s fundamental resonant mode, resulting in a wide impedance bandwidth. From the results, it can be seen that an enhanced impedance bandwidth is obtained when the loading strip length $\ell_1$ is chosen such that $\ell_1/\ell_2$ is in a range of approximately 0.6–0.8 ($\ell_2$: protruding signal strip length). The maximum impedance bandwidth is as large as 1410 MHz or approximately 62.9%, centered at roughly 2.2 GHz, which is also roughly two times that of an antenna without the loading strips ($\ell_1 = 0$).

So far, we have restricted our discussion to rectangular slot antennas. In contrast, Li et al. have studied elliptical/circular slot antennas for UWB applications, where a U-shaped tuning stub [17] is employed [18]. Two types of feed systems, the microstrip line and the CPW systems, are investigated. The antenna geometry is illustrated in Fig. 9, and the measured and simulated bandwidths of the return loss are tabulated in Table 1. These values meet the requirements for UWB applications.

### III. WIRE ANTENNAS

#### A. Integral Equations for Wire Antenna Analysis

In 1965, Mei derived an integral equation for an arbitrarily shaped wire of length $L$ [19]

$$\int_0^L \hat{I}(s') \pi X_{\text{Mei}}(s, s') ds' = B \cos \beta s - \frac{j}{Z_0} \int_0^L E_\xi \sin \beta(s - \xi) d\xi$$

(1)
where the wire is in free space, and \( I(s') \) is an unknown current. The integral kernel \( \pi^{Mei}(s, s') \) in (1) involves integral and differential calculations. Fourteen years later, the kernel \( \pi^{Mei}(s, s') \) was transformed into a closed kernel \( \pi^{Nakano} \) (without any integral and differential calculations) [20], [21], which remarkably reduced the computation time and facilitated more extensive wire antenna analysis.

In 1981, Rana and Alexopoulos derived an integral equation for a straight wire antenna printed on a dielectric substrate [22], and in 1988, Nakano et al. derived an integral equation for an arbitrarily shaped wire on a dielectric substrate [23], based on

\[
\int_0^L I(s') \left[ -\frac{\partial}{\partial s} \left( \Pi'(s, s') - \Pi(s, s') \right) + k_0^2(s \cdot s')\Pi(s, s') \right] ds' = -E_i(s) \quad (2)
\]

where \( \Pi'(s, s') \) and \( \Pi(s, s') \) are Hertz vector potential functions, which include surface wave effects. Equation (2) has been solved using the method of moments (MoM) [24], where each of the impedance matrix elements \( Z_m,n \) \( (m = 1, 2, \ldots, N; n = 1, 2, \ldots, N) \) is composed of four terms, all involving a triple integral calculation. In 2005, these four terms were reduced to three terms: one involving a single integral calculation, one a double integral calculation, and one a triple integral calculation, thereby dramatically reducing the computation time [25]. Note that an integral equation for an arbitrarily shaped wire antenna on a dielectric half-space was also derived in 1998 [26].

B. Representative Wire Antennas

1) Loop Antenna: A square loop antenna has a simple resonant structure [27], [28]. Fig. 10(a) shows an antenna system composed of \( N \) discrete square loops (antenna height \( h = 1 \) cm). Analysis based on an integral equation reveals that each of the loops resonates when its circumference is approximately one wavelength [29]. It follows that a discrete multiloop (ML) antenna has minima in the frequency response curve of the VSWR, as shown in Fig. 10(b). In other words, the discrete ML acts as a multiband antenna.
When the \( N \) square loops are connected by wires at the four loop corners, this modified loop has a relatively wide characteristic with respect to the VSWR: an approximately 16% bandwidth (VSWR = 2 criterion) for \( N = 7 \), which is more than 2.5 times the bandwidth of a single-loop antenna (\( N = 1 \)).

Note that the loops (radiation elements) are coupled to the coaxial feed line electromagnetically via an inverted L-line, as shown in Fig. 10(c). This is called Nakano coupling (L-line coupling), which was first applied to a C-figured loop antenna in 1995 [30]. The advantage of Nakano coupling is that it eases impedance matching [31], leading to a wide impedance bandwidth. [32]–[35].

2) Spiral Antenna: The radiation mechanism of a spiral antenna suspended in free space was first qualitatively explained using current band theory [36], and later quantitatively described using the current distribution based on an integral equation [21]. The spiral radiates a CP wave in the two directions normal to the spiral plane (bidirectional radiation), due to the outgoing current decaying from the feed point to the arm ends. Thanks to the decaying current, the antenna exhibits almost constant input impedance over a wide frequency range.

For practical applications, the bidirectional radiation is transformed into unidirectional radiation by placing a conductive reflector (or a cavity) behind the spiral. Generally, as the distance between the spiral and the reflector (antenna height) is decreased, the inherent wideband antenna characteristics degrade due to increase in reflected currents from the antenna arm ends. However, this degradation can be mitigated by connecting resistors to the antenna arm ends or by placing an absorbing strip (ABS: see Fig. 11) behind the outermost portion of the arms [38]. A spiral antenna having an antenna height of less than \( \lambda/10 \) (\( \lambda \): the wavelength at the lowest operating frequency) attains a frequency bandwidth of more than 1 : 3, satisfying both a 3-dB axial-ratio criterion and a VSWR = 2 criterion [39].

3) Helical Antenna: The current distribution of an axial-beam helical antenna [40] has been analyzed using an integral equation [41]. It is found that there are two distinct regions: one region (C-region) from the feed point to a point near the end of the second turn, and the other region (S-region) just after the C-region, as shown in Fig. 12. The current distributed along the C-region generates backfire radiation toward the conducting flat reflector. This backfire radiation is reflected by the flat reflector, and then excites the S-region, inducing a traveling wave current whose amplitude is almost constant, except near the arm end. In other words, the C-region acts as an exciter and the S-region acts as a director (a waveguide element).

There are two findings for this antenna: 1) the helical antenna can work even when these two regions are disconnected; and 2) a helical antenna with a small number of turns constituting only the C-region radiates a CP wave. The latter finding leads to the realization of a low-profile helix as a CP element, using the combination of a small number of turns and a low pitch angle. Nakano et al. [42] describe a two-turn helix of \( 4^\circ \) pitch angle that exhibits a 12% bandwidth for a 3-dB axial-ratio criterion.

4) Inverted F-Antenna: An inverted F-antenna (IFA), which is considered a modified version of an inverted F-antenna, was first proposed in 1963 [43]. The advantage of this antenna is that it exhibits a CP wave over a wide frequency range by using an inverted inverted F-line.
L-antenna or a bent monopole antenna [43], has an antenna height of approximately $\lambda/10$ ($\lambda$: wavelength) above a conducting reflector [perfect electric conductor (PEC)]. For practical applications in portable devices, the antenna height must be as small as possible. It has been found that the antenna height can be decreased from $\lambda/10$ [44], without deteriorating the input impedance characteristic, if the PEC reflector is replaced with an electromagnetic band gap (EBG) reflector [45]. This is attributed to the fact that the reflection coefficient at the EBG surface is $1$ (in-phase reflection). The antenna height above the EBG reflector surface in Fig. 13(a) is extremely small: $0.01\lambda$.

In this case, the IFA forms a tilted beam toward the $-x$ space, as shown in Fig. 13(b), due to the induced current on the EBG surface, whose phase is delayed toward the negative $x$-direction.

In [46], four IFAs (IFA$_{+x}$ on $\pm x$-axis, IFA$_{+y}$ on $\pm y$-axis) are arrayed symmetrically with respect to the origin of an EBG reflector. If the IFA$_{+x}$ (IFA$_{+y}$) is excited with the other three being parasitic, the beam is tilted toward the $-x$ ($+x$) space. Similarly, if the IFA$_{+y}$ (IFA$_{+y}$) is excited with the other three being parasitic, the beam is tilted toward the $-y$ ($+y$) space. Thus, four beam directions are selected by changing the feed point. Thus, a steerable beam antenna [47] is realized.

5) Composite Helical and Spiral Antenna: An antenna that radiates a tilted beam is often required in applications, such as mobile communications systems, satellite communications systems, and wireless local area network (LAN) systems. In response to this requirement, a low-profile composite helical and spiral (CHES) antenna, shown in Fig. 14(a), has been developed [48]. A tilted beam is formed using the phase difference in the currents flowing along the helical arm and the spiral arm, connected to the end of the helical arm. Fig. 14(c) shows a representative radiation pattern. A detailed analysis reveals that the angle of maximum radiation in the elevation plane, i.e., tilt angle $\theta_{\text{max}}$, remains relatively un-

changed as a function of frequency; $\theta_{\text{max}}$ is between $28^\circ$ and $34^\circ$ for a design frequency range of 11.7–12.75 GHz (Ku-band for satellite communications), where an antenna height is approximately 6 mm. Within this frequency range, the axial ratio in the beam direction is less than $3$ dB, the input impedance is almost constant, and the gain reduction is very small.

C. Wire Antenna Array

A high-gain antenna system can be realized using an array technique, where each array element is connected to the feed point by a transmission line. In the microwave frequency band, a microstrip line [49] is commonly used as the transmission line for the array antenna. This line is, in general, lossy due to the dielectric substrate on which the strip line is printed. In addition, the microstrip line radiates energy while delivering power from the feed point to the array elements. These factors reduce the radiation efficiency, and hence, the aperture efficiency.

To overcome this issue of low radiation efficiency, a wireless feed system (electromagnetic coupling feed system) can be adopted for the wire antenna array. Fig. 15(a) shows such an array, where curl antennas are arrayed above a circular cavity [50]. The distance between the upper and lower parallel plates of the cavity is less than one half-wavelength. The vertical section of each curl antenna is inserted into the cavity to receive power radiated from a feed probe located at the center of the lower plate. The excitation amplitude of each curl antenna is controlled by the insertion length of the vertical section into the cavity, while the excitation phase is controlled by the rotation angle around the vertical section. Both the uniform amplitude condition and the in-phase condition are realized by using a vector rotation method.
[51], thereby the array has maximum directivity in the z-axis direction. Fig. 15(b) shows the measured gain for a 168-curl antenna array, together with the aperture efficiency $\eta$; the maximum aperture efficiency reaches an unrivaled value of more than 90%. This curl array antenna has been used as a Ku-Band direct-broadcasting-satellite-receiving antenna, where the antenna height above the cavity surface is 3.8 mm.

Note that the technique used for the curl antenna array has also been applied to an axial-mode helical antenna array, which is designed for the S- and X-band feeds of a VLBI Exploration of Radio Astronomy (VERA) antenna [52].

The radiation from the aforementioned curl and helical antenna arrays is circularly polarized. In contrast, the radiation from a wire grid array antenna (GAA), shown in Fig. 16(a), is linearly polarized. Recent analysis, based on the MoM with (2) and the finite-difference time-domain method (FDTDM) [53], reveals that the current along the grid wire on a dielectric substrate (thickness of 1.32 mm) exhibits a standing wave behavior, as shown in Fig. 16(b), where the GAA is fed from its center point in balanced mode [25]. The maximum radiation in this case is in the direction normal to the grid array plane (broadside beam). It is noted that the bandwidth for a VSWR = 2 criterion under the broadside radiation is widened, when negative effects due to the dielectric substrate (surface waves generation) are deleted; an approximately 12% bandwidth is obtained in [54].

### IV. CONCLUSION

Recently developed printed slot and wire antennas have been reviewed. Narrow-slot and wide-slot antennas fed from a microstrip line can be modified to enhance the working bandwidth. Some antennas for generating a CP beam have also been introduced. A widened tuning stub is used to enhance the bandwidth of slot antennas fed by a CPW.

Wire antenna analysis methods have been described and the radiation characteristics of loop, spiral, helical, inverted F, and CHES antennas have been discussed. A curl antenna array with an unrivaled aperture efficiency of more than 90% has been presented.

### Acknowledgment

The authors would like to thank V. Shkawrytko and H. Mimaki for their assistance in the preparation of this manuscript.

### REFERENCES


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