Mesh Antennas for Dual Polarization

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Abstract—Three mesh antennas, all having an extremely small antenna height of approximately 0.06 wavelength above a ground plane, are presented. First, a mesh antenna excited with a balanced feed is analyzed. It is revealed that the mesh antenna radiates a linearly polarized wave with no cross-polarization component in the principal planes. The radiation mechanism is explained using the current distribution. Second, a mesh antenna excited with an unbalanced feed is analyzed. This antenna shows almost the same radiation characteristics as the mesh antenna with a balanced feed. The frequency bandwidth for a VSWR = 2 criterion is evaluated to be approximately 3%. Third, a mesh antenna having two perturbation elements is analyzed. It is found that the antenna acts as a radiation element of circular polarization. The frequency bandwidth for a 3-dB axial ratio criterion is calculated to be approximately 1%. The mesh antennas in the first and second analyses can be used as dual linear polarization elements by appropriately switching the feed. Similarly, the mesh antenna in the third analysis can be used as a dual circular polarization element by switching the feed.

Index Terms—Circular polarization, dual polarization, linear, wire antenna.

I. INTRODUCTION

A LOOP antenna is a fundamental radiation element [1]–[4], which is usually made of a conducting wire and located in free space. Recently, loops printed on a dielectric substrate have been analyzed [5], [6]. The analysis has shown that the loop can radiate both linearly polarized [5] and circularly polarized [6] waves.

This paper presents a mesh antenna, which is regarded as an extension of the loop antenna. The purpose of this paper is to investigate the radiation characteristics of the mesh antenna as a dual linearly polarized antenna and a dual circularly polarized antenna.

The prototype of the mesh antenna is composed of a square loop ABCD and four wires added to the loop, as shown in Fig. 1(a). This antenna is excited from the center region of the antenna with a balanced feed. The antenna is designated as the mesh antenna with balanced feed (MA-B). First, the MA-B is analyzed by using the method of moments (MoM) [7], [8]. A limitation of the MoM is brought to light in its application to an integral equation derived for an arbitrarily shaped thin wire [9], whose radius $\rho$ satisfies $\rho \ll \lambda_0$ (free space wavelength) at a test frequency of 4 GHz. The kernel of the equation is expressed in closed form after the thin wire is subdivided into numerous segments, each being regarded as a line. The length of each segment is always chosen to be greater than $2.5\rho$. This choice gives good convergence of the current distribution. In other words, the relationship between the length and radius of each segment limits the application of the MoM to the integral equation. Note that piecewise sinusoidal functions are adopted for the expansion and weighting functions of the MoM.

The radiation pattern, input impedance, VSWR, and gain are evaluated on the basis of the obtained current distribution. The positive direction of the current flow in Figs. 2, 5, and 9 corresponds to the direction from bottom to top on the vertical axis.
Fig. 1. Mesh antennas: (a) with balanced feed, MA-B; (b) with unbalanced feed, MA-U; either terminal \(a_f\) or \(b_f\) is used as the feed point; terminals \(c_g\) and \(d_g\) are in contact with the ground plane; and (c) with perturbation elements, MA-UP; either terminal \(a_f\) or \(b_f\) is used as the feed point; terminals \(c_g\) and \(d_g\) are in contact with the ground plane.

(where letters are used for representing the configuration) and left to right on the horizontal axis.

III. MESH ANTENNA WITH BALANCED FEED (MA-B)

The prototype of a mesh antenna for a radiation element of dual linear polarization is investigated in this section. Based on this prototype, two mesh antennas are constructed in Sections IV and V.

A. Configuration

Fig. 1(a) shows the configuration of an MA-B. The distance between the conducting plane and mesh (called the antenna height) is designated as \(h\), and the mesh peripheral length for the square loop \(ABCD\) (where \(AB = BC = CD = DA\)) is designated as \(8s\). The side lengths are chosen to be \(A\Delta = d\Delta B = B\Delta C = C\Delta D = D\Delta A = s\). The distance between terminals \(a\) and \(c\) is assumed to be infinitesimal (delta gap). The distance between terminals \(b\) and \(d\) is also assumed to be infinitesimal.

The antenna height for the MA-B is arbitrarily chosen: \(h = 0.0635\lambda_0\). The peripheral length \(8s\) of an MA-B with this height \(h\) is optimized such that the MA-B has an almost resistive impedance of 50 \(\Omega\) at a test frequency of \(f_0 = 4\) GHz, resulting in \(8s = 1.272\lambda_0\).
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Fig. 2. Current distribution of the MA-B when terminals α and ε are excited with a delta-gap source of 1 V and terminals β and δ are open-circuited. Currents along the (a) x-directed wires and (b) y-directed wires.

B. Radiation Characteristics of MA-B

The MA-B is excited by a balanced feed. Let the terminals α and ε be excited with a delta-gap source of 1 V and the terminals β and δ be open. Fig. 2 shows the current distribution (|I|) is the amplitude of current $I = I_α + jI_ε$). Note that the current does not flow along the x-directed center wires b'd' and α'd', and therefore Fig. 2 excludes the numerical results for the currents along these wires.

The currents along the x-directed wires A'd' and B'd' are symmetrical with respect to the junction point c' [see Fig. 2(a)]. Similarly, the currents along the x-directed wires Dc' and Cc' are symmetrical with respect to the junction point c'. These symmetrical currents lead to the cancellation of the radiation fields from all the x-directed wires (x-polarized radiation fields) in the z-direction.

The current distributions along the y-directed wires A'D and B'C have the same amplitude and phase [see Fig. 2(b)]. These are almost the same as the current distribution along the y-directed center wire α'd'c'd' that has the source point. It follows that the radiation fields of y-polarization due to these three currents add in the z-direction, forming the radiation pattern shown in Fig. 3(a). The half-power beam width (HPBW) of the copolarization component is approximately 75° in the $\phi = 0°$ plane (in the x-z plane) and 63° in the $\phi = 90°$ plane (in the y-z plane). Cross-polarization components do not appear in either plane.

The measured radiation patterns (white dots for $E_\phi$ and black dots for $E_\theta$), which are presented in Fig. 3(a), agree with the theoretical results. For the measurement, a large ground plane of 12λ₀ × 2λ₀ is used to approximate a theoretical ground plane of infinite extent. Note that the measurements performed throughout this paper use this ground plane. (Preliminary calculations for a finite-size ground plane using the finite-difference time-domain method [10]–[12] show that the radiation pattern and input impedance are not significantly affected when the size of the ground plane is larger than approximately 2λ₀ × 10cm. For reference, the theoretical radiation pattern for a ground plane of approximately 2λ₀ × 2λ₀ is shown in Fig. 3(b). Also, note that the present mesh antenna is supported by a honeycomb material spacer with a relative permittivity of $\varepsilon_r \approx 1$, as mentioned in Section II, and hence the effects of surface waves on the radiation characteristics can be neglected, unlike antennas printed on a dielectric substrate with $\varepsilon_r > 1$.)

Further calculations reveal that the frequency bandwidth for a VSWR = 2 (relative to 50 Ω) criterion is approximately 3%. The gain over this bandwidth is approximately 9.5 dB.

The above-mentioned results have been obtained under the condition that terminals α and ε are excited and terminals β and δ are open. Points to be noted are that there is no current flowing along the x-directed center wires b'd' and c'd' and the radiation is linearly y-polarized with no cross-polarization component. Since the antenna has a symmetrical configuration with respect to the mesh center point, when terminals α and ε are excited and terminals β and δ are open and terminals b and d are excited, as opposed to the previous case, the radiation is linearly x-polarized. The same VSWR and gain characteristics as those for the y-polarization are reproduced for
the \( x \)-polarization. In other words, the MA-B can be used as a radiation element of dual linear polarization by switching the feed.

IV. MESH ANTENNA WITH UNBALANCED FEED (MA-U)

Although not illustrated in Fig. 1(a), the MA-B in the previous section requires balun circuits to realize a balanced feed. To avoid the complexity of using balun circuits for the feed, a modified mesh antenna, which is fed from coaxial lines without balun circuits, is proposed and analyzed in this section.

A. Configuration

As shown in Fig. 1(b), the mesh antenna is modified to have four vertical wires \( a_f, b_f, c_f, \) and \( d_f \). Either terminal \( a_f \) or \( b_f \) can be used as a feed point. The other terminals \( c_f \) and \( d_f \) are in contact with the ground plane (short-circuited). The distance between terminals \( a_f \) and \( c_f \) (or \( a_f \) and \( b_f \)), \( \Delta_{ac} \), is chosen to be the same as that between terminals \( b_f \) and \( d_f \) (or \( b_f \) and \( d_f \)), \( \Delta_{bd} \). This antenna is distinguished from the previous MA-B and designated as the MA-U. It should be emphasized that the MA-U has a simpler feed system than the MA-B.

For comparison, the antenna height \( h \) of the MA-U is chosen to be the same as that for the previous MA-B: \( h = 0.0635 \lambda_0 \). The MA-U is optimized to have an input impedance of approximately 50 \( \Omega \) at a test frequency of \( f_0 = 4 \) GHz, as in the MA-B. This is performed by changing the distance between the feed points \( \Delta_{ac} (= \Delta_{bd}) \). Fig. 4 shows the VSWR (relative to 50 \( \Omega \)) as a function of \( \Delta_{ac} \) for three different loop peripheral lengths: \( 8s = 1.264 \lambda_0 \) and \( 1.264 \lambda_0 \times (1 \pm 0.03) \). Based on this calculation, \( \Delta_{ac} = 0.06 \lambda_0 \) and \( 8s = 1.264 \lambda_0 \) are adopted in the following calculations. Note that the optimized loop peripheral length of the MA-U is very close to that for the MA-B.

B. Radiation Characteristics of MA-U

The MA-U shown in Fig. 1(b) is analyzed under the condition that terminal \( a_f \) is excited and terminal \( b_f \) is open-circuited. The obtained current distribution is shown in Fig. 5. The currents along the \( x \)-directed wires \( b'b \) and \( d'd' \) are very small, as shown in Fig. 5(a). Therefore, it can be said that the situation observed in the previous MA-B (that is, the currents along the \( x \)-directed wires \( b'b \) and \( d'd' \) are zero) is approximately reproduced in the MA-U. This contributes to reducing the cross-polarization component in the radiation pattern.

Fig. 6(a) and (b) shows the radiation patterns in the \( \phi = 0^\circ \) and \( \phi = 90^\circ \) planes, respectively. The measured data (white dots for \( E_\phi \) and black dots for \( E_\theta \)) are also presented in these figures, showing good agreement with theoretical values.

In the \( \phi = 0^\circ \) plane, \( E_\phi \) (dashed line) is the copolarization component and \( E_\theta \) (solid line) is the cross-polarization component, as shown in Fig. 6(a). The copolarization component
Fig. 6. Radiation pattern of the MA-U when terminal \( a_f \) is excited and terminal \( b_f \) is open-circuited. (a) Total radiation pattern in the \( \phi = 0^\circ \) plane, (b) total radiation pattern in the \( \phi = 90^\circ \) plane, (c) local radiation component \( E_{\theta} \) from \( y \)-directed wires \( AD \), \( d'a-c'e' \), and \( BC \), calculated in the \( \phi = 90^\circ \) plane, (d) local radiation component \( E_{\theta} \) from \( z \)-directed wires \( \alpha \rho \), \( b_f \), \( c_f \), and \( d_f d \), calculated in the \( \phi = 90^\circ \) plane. Theoretical \( E_{\theta} \) —, measured \( E_{\theta} \) • • •, theoretical \( E_{\phi} \) —, and measured \( E_{\phi} \) o o o.

\( E_{\phi} \) is generated from the currents along the \( y \)-directed wires \( AD \), \( d'a-c'e' \), and \( BC \), which are almost in-phase, as shown in Fig. 5(b). The cross-polarization component \( E_{\phi} \) in the \( \phi = 0^\circ \) plane is generated from the currents along the \( x \)-directed wires \( BA \), \( b_f b \), \( d_f d \), and \( CD \) [see Fig. 5(a)] and \( z \)-directed wires \( \alpha \), \( b_f b', c_f c' \), and \( d_f d \) [see Fig. 5(c)]. The cross-polarization component is desirably low (theoretical value: \(-27 \text{ dB} \) on the \( z \)-axis), as expected from the current phase relationships.

In the \( \phi = 90^\circ \) plane, \( E_{\theta} \) (solid line) is the copolarization component and \( E_{\phi} \) (dashed line) is the cross-polarization component, as shown in Fig. 6(b). Note that the currents along the \( y \)- and the \( z \)-directed wires generate the copolarization component \( E_{\theta} \) in the \( \phi = 90^\circ \) plane. The \( E_{\theta} \) shown in Fig. 6(b) can be decomposed into two local radiation components: the radiation from the \( y \)-directed wires [see Fig. 6(c), calculated using Fig. 5(b)] and the radiation from the \( z \)-directed wires \( \alpha \rho \), \( b_f b' \), \( c_f c' \), and \( d_f d \) [see Fig. 6(d), calculated using Fig. 5(c)]. It is found that the currents along the \( z \)-directed wires slightly affect the symmetry of the radiation pattern in Fig. 6(c) produced by the currents along the \( y \)-directed wires, resulting in a small lobe near the \( y \)-axis, as shown in Fig. 6(b).

The small cross-polarization component \( E_{\phi} \) in the \( \phi = 90^\circ \) plane appears due to the fact that the currents along the \( x \)-directed wires \( BA \), \( b_f b \), \( d_f d \), and \( CD \) are not perfectly symmetrical with respect to their middle points, as shown in Fig. 5(a). The amplitude values of the currents at symmetrical points with respect to the middle point of each \( x \)-directed wire are not identical (although they are almost the same), and a phase difference of exactly \( 180^\circ \) is not obtained at these symmetrical points (although a phase difference of approximately \( 180^\circ \) is obtained), as shown in Fig. 5(a).

The HPBW of the copolarization component is approximately \( 74^\circ \) in the \( \phi = 0^\circ \) plane and \( 60^\circ \) in the \( \phi = 90^\circ \) plane. Note that these HPBWs are close to those of the MA-B.

The frequency responses of the VSWR and gain are presented in Figs. 7 and 8, respectively, together with measured values (black dots). For comparison, the VSWR and gain of the MA-B are included (illustrated by dashed lines). It is clear that the MA-U has almost the same performances as the MA-B. The frequency bandwidth for a VSWR = 2 criterion is calculated to be approximately 3% with a maximum gain of 9.7 dB.
The results shown above have been obtained under the condition that terminal \( a_f \) is excited and terminal \( b_f \) is open-circuited, to obtain a linearly \( y \)-polarized wave. When terminal \( a_f \) is open-circuited and terminal \( b_f \) is excited, the antenna radiates a linearly \( x \)-polarized wave, reproducing the same VSWR and gain characteristics as those for the \( y \)-polarization. Thus, the MA-U is a radiation element of dual linear polarization, whose polarization can be switched by switching the feed point.

V. MA-U WITH PERTURBATION ELEMENTS (MA-UP)

So far, mesh antennas for dual linear polarization have been discussed. Now, a mesh antenna for dual circular polarization is investigated.

A. Configuration

When the MA-U shown in Fig. 1(b) is simultaneously excited from the two terminals \( a_f \) and \( b_f \) with equal amplitude and a 90° phase difference (this two-terminal simultaneous excitation is realized by using phase-delay circuits or phase shifters), the MA-U radiates a circularly polarized wave. In this section, single-terminal excitation of either \( a_f \) or \( b_f \) without any phase shifters, which is an obviously simpler excitation than the two-terminal simultaneous excitation, is considered to obtain a circularly polarized wave. For this, two perturbation elements [6], [13] are added to the MA-U, as shown in Fig. 1(c), where the perturbation elements are specified by length \( \delta \) and orientation angle \( \alpha \). This antenna is designated as MA-UP.

Throughout the following Sections V-B and -C, the distance between the feed points \( \Delta_{xc} (= \Delta_{kd}) \) and the antenna height \( h \) are taken to be the same as those of MA-U in Section IV \( (\Delta_{xc} = \Delta_{kd} = 0.06\lambda_0 \) and \( h = 0.0635\lambda_0) \). The mesh peripheral length \( 8s \), perturbation element length \( \delta \), and orientation angle \( \alpha \) are changed subject to the objectives of the analysis.

B. Radiation Characteristics of MA-UP

The mesh peripheral length \( 8s \), perturbation element length \( \delta \), and orientation angle \( \alpha \) are fixed: \( 8s = 1.264\lambda_0 \) (same as for MA-U), \( \delta = 0.006\lambda_0 \equiv \delta_0 \), and \( \alpha = 45^\circ \). Preliminary calculations reveal that when terminal \( a_f \) is excited and terminal \( b_f \) is open-circuited, MA-UP has standing-wave current distributions similar to those for MA-U, shown in Fig. 5. The perturbation elements in this case do not contribute to generating a traveling-wave current along the mesh periphery \( ABCDA \). In other words, MA-UP with terminal \( b_f \) open-circuited cannot radiate a circularly polarized wave. Based on this fact, terminal \( b_f \) is connected to the ground plane in the following discussions.

Fig. 9(a) shows the current amplitude \( |\Pi| \) and phase along the mesh periphery \( ABCDA \) when the minimum axial ratio is obtained at a relative frequency of \( f/f_0 = 0.984 \). The discontinuity points in the amplitude correspond to the wire branch points, where Kirchhoff’s current law is satisfied. The variation in the amplitude is small (6 mA ± 1.57 mA). The phase changes by 360° along the periphery \( ABCDA \). The local radiation from the periphery, therefore, contributes to generating a circularly polarized wave (a right-hand CP wave), as shown in Fig. 10(a). Note that the solid line in Fig. 10 shows the right-hand circularly polarized wave component of the radiation field \( E_R \) and the dashed line shows the left-hand circularly polarized wave component \( E_L \) (cross-polarization component).

The current amplitude and phase along the four wires inside the periphery \( ABCDA \) are shown in Fig. 9(b). These currents indicate almost the same amplitude with an approximately –90° phase progression (the phase difference between the currents along neighboring wires is approximately 90°). It follows that these currents radiate a circularly polarized wave (a right-hand CP wave), as shown in Fig. 10(b). Thus, the total radiation field [Fig. 10(a) plus (b)] is also circularly polarized, as shown in Fig. 10(c).

The dashed line in Fig. 11 shows the frequency response of the axial ratio. The frequency bandwidth for a 3-dB axial ratio criterion is approximately 1%. It is possible to shift the frequency \( f/f_0 = 0.984 \) for the minimum axial ratio to the frequency \( f_0(f/f_0 = 1) \) by slightly decreasing the peripheral length from \( 8s = 1.264\lambda_0 \) to \( 1.240\lambda_0 \). This is shown by a solid line in Fig. 11, which indicates almost the same 3-dB axial ratio bandwidth (approximately 1%). The measured results are also presented with black dots. Within this 3-dB axial ratio bandwidth for a decreased peripheral length of \( 8s = 1.240\lambda_0 \), the theoretical VSWR shows values of less than 1.3 (see the dashed line in Fig. 12) with a theoretical gain of approximately 9.5 dB (see the dashed line in Fig. 13). This gain is very close to those for the MA-B and MA-U. Note that the theoretical VSWR and gain agree with measured results illustrated by black dots.

The above-mentioned radiation characteristics for right-hand circular polarization have been obtained when terminal \( a_f \) is excited and terminal \( b_f \) is grounded. With the opposite excita-
Fig. 10. Radiation pattern of the MA-UP in the $\phi = 0^\circ$ plane; $s = 1.240 \lambda_0$, $\delta = 0.06 \lambda_0$, and $\alpha = 45^\circ$. Terminal $a_f$ is excited with terminal $b_f$ grounded. Theoretical $\cdots$, measured $\bullet \bullet \bullet$.

Fig. 11. Frequency response for the axial ratio of the MA-UP; $s = 1.240 \lambda_0$, $\delta = 0.06 \lambda_0$, and $\alpha = 45^\circ$. Terminal $a_f$ is excited with terminal $b_f$ grounded. Theoretical $\cdots$, measured $\bullet \bullet \bullet$.

Fig. 12. Frequency response for the VSWR of the MA-UP; $s = 1.240 \lambda_0$, $\delta = 0.06 \lambda_0$, and $\alpha = 45^\circ$. Terminal $a_f$ is excited with terminal $b_f$ grounded. Theoretical $\cdots$, measured $\bullet \bullet \bullet$.

Fig. 13. Frequency response for the gain of the MA-UP; $s = 1.240 \lambda_0$, $\delta = 0.06 \lambda_0$, and $\alpha = 45^\circ$. Terminal $a_f$ is excited with terminal $b_f$ grounded. Theoretical $\cdots$, measured $\bullet \bullet \bullet$.

Fig. 14. Axial ratio of the MA-UP as a function of orientation angle $\alpha$; $s = 1.240 \lambda_0$ and $\delta = 0.06 \lambda_0$. Terminal $a_f$ is excited with terminal $b_f$ grounded. be $s = 1.240 \lambda_0$ (used in Figs. 11–13), and the perturbation element length $\delta$ and orientation angle $\alpha$ are changed.

Fig. 15 shows the changes in the gain and VSWR for a right-hand circularly polarized wave when the perturbation element length is made longer ($\delta_L = \delta_0 + 0.02 \lambda_0$) and shorter ($\delta_S = \delta_0 - 0.02 \lambda_0$) than the initial value $\delta_0 = 0.06 \lambda_0$. Two facts are revealed as the perturbation element length increases: 1) the frequency at which the gain shows a maximum value becomes lower and 2) the VSWR in the lower frequency region improves. Fig. 16 shows the axial ratios for these two perturbation element lengths $\delta_L$ and $\delta_S$ as a function of frequency.
It can be said that the frequency at which the axial ratio shows a minimum value becomes lower as the perturbation element length increases.

VI. CONCLUSION

The radiation characteristics of three mesh antennas (MA-B, MA-U, and MA-UP), including the radiation pattern, gain, and VSWR, have been calculated on the basis of the current distributions obtained by using the method of moments.

The MA-B is fed from the middle point of a y-directed center wire. The three currents along the y-directed wires have almost the same amplitude and phase. In this case, currents along the x-directed center wires do not exist. Thus, the polarization of the radiation is in the y-direction. By virtue of the symmetrical configuration with respect to the antenna center point, a linearly x-polarized wave is also obtained by switching the feed point.

The MA-U is a modified version of the MA-B. The four terminals of the MA-B are reduced to two for the MA-U. The advantage of the MA-U is that a dual linearly polarized wave can be obtained with a simplified feed system. The analysis reveals that the cross-polarization component is desirably low (−27 dB on the z-axis). The HPBW of the copolarization component is approximately 74° in the φ = 0° plane and 60° in the 90° plane, which are close to those of the MA-B. The MA-U has almost the same frequency responses for the VSWR and gain as the MA-B.

The MA-UP, which is an extension of the MA-U, is proposed as a radiation element of dual circular polarization. The MA-UP has two perturbation elements to obtain a traveling-wave current along the mesh periphery. It has been revealed that both the mesh periphery and the four wires inside the mesh periphery generate circularly polarized waves. The frequency bandwidth for a 3-dB axial ratio criterion is approximately 1% for an extremely low antenna height of 0.0635λ0. Within this bandwidth, the VSWR shows values of less than 1.3 with a gain of approximately 9.5 dB. This gain is close to those of the MA-B and MA-U.

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REFERENCES

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