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YOSHIZAWA, Akihiro / YAMAUCHI, Junji / NAKANO, Hisamatsu

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Characteristics of a Crossed-Wire Scatterer Without a Junction Point for an Incident Wave of Circular Polarization

HISAMATSU NAKANO, MEMBER, IEEE, AKIHIRO YOSHIZAWA, AND JUNJI YAMAUCHI

***Abstract*—A crossed-wire scatterer has the wires displaced in the backscattering direction, and is able to scatter an incident wave of circular polarization in such a way that the backscattering wave has the same rotational sense as that of the incident wave. The radiation performance of the scatterer is improved by bending the horizontal and the vertical wires. Arrays consisting of crossed-wire scatterers are constructed and the backscattering cross sections (BSCS's) are calculated. It is revealed that the increase in the current amplitude due to the mutual effects among the array elements contributes to enhancement in the BSCS. It is also shown that a maximum value of the BSCS of an array of 3 × 3 bent crossed-wire scatterers is 1.8 times as large as that of a dihedral corner reflector which has the same aperture area. The BSCS's as a function of the angle of incidence are presented with experimental results at a frequency of 9.375 GHz.**

I. INTRODUCTION

TWO STRAIGHT wires joined at a junction were analyzed because of an interesting configuration for scattering problems. Taylor *et al.* [1], for example, numerically analyzed a crossed-wire configuration using an integral equation technique. The same configuration was treated by Chao and Strait [2] and the current distributions on the crossed-wire configurations were discussed. A subsequent study was made by Butler [3], who presented numerical results of a pair of skew crossed wires and compared his data for the special case of perpendicular wires with those evaluated by Taylor and Chao. In King's recent papers [4], [5], zero-order and first-order solutions were derived for the currents induced on crossed wires illuminated by an obliquely incident plane wave. From the point of view of application to a frequency-selective reflector, Agrawal and Imbriale [6] and Pelton and Munk [7] calculated scattering from periodic arrays of crossed dipoles.

The motivation in the present paper arises from a desire to apply a crossed-wire scatterer to a reflector for a radar system using a circularly polarized wave (CPW-radar). The problem to be treated here is different from those of [1]-[7] in that a crossed-wire scatterer does not possess a junction point, and in that an incident wave of circular polarization illuminates the scatterer.

In the CPW-radar system a single antenna with a circular polarizer is used concurrently as a transmitting antenna and a receiving antenna. Therefore, a reflector for the CPW-radar must generate a reflected wave of circular polarization with the same rotational sense as that of an incident wave of circular polarization. If a metallic planar plate is used as a reflector, the backscattering wave from the reflector is not detected in the CPW-radar, because the backscattering wave has the rotational sense opposite to that of the incident wave. This situation is often called "single reflection." If a crossed-wire scatterer has a junction point, it acts merely as a reflector of the single reflection for a circularly polarized wave.

The purpose of this paper is to explore the possibility that a crossed-wire scatterer without a junction point acts as a reflector whose performance corresponds to a dihedral corner reflector [8], in which the backscattering wave has the same rotational sense as that of an incident wave of circular polarization by virtue of double reflection. The current distributions are calculated for straight and bent crossed-wire scatterers using the method of moment [9]. The backscattering cross sections (BSCS's) are evaluated from the scattering fields obtained using the current distributions.

Enhancement in the BSCS is also demonstrated using an array technique. A comparison between an array of bent crossed-wire scatterers and a dihedral corner reflector with the same aperture area shows that the array has a larger BSCS with a thinner structure. Some experimental results are presented with good agreement with theoretical ones.

II. NUMERICAL RESULTS OF A SINGLE STRAIGHT CROSSED-WIRE SCATTERER

Attention is focused on the backscattering wave from a single straight crossed-wire scatterer to obtain basic data. The configuration of the scatterer is shown in Fig. 1. Both the horizontal and the vertical wires are half-wavelength in length, i.e., $2L_1 = 2L_2 = \lambda/2$, where λ is the wavelength of an incident wave. In the following analysis a wavelength of $\lambda = 0.032$ [m] (a frequency of 9.375 GHz) is used. Each wire is perfectly conducting, and is thin relative to its length as well as to the wavelength of the incident wave (the radius of the wires, a_0, is 0.00469 λ). The spacing between the horizontal and the vertical wires is designated S.

Fig. 2 shows typical current distributions under the condition that the scatterer is illuminated by a plane wave of circular polarization of left-handed sense from the z-axis direction (the angle of incidence $\theta = 0°$), or by an electric field of $\overline{E}^{\text{in}} = E_0(\hat{\theta} - j\hat{\phi}) \exp(j\beta z)$, where $\hat{\theta}$ and $\hat{\phi}$ are unit vectors of spherical coordinates, and $\beta = 2\pi/\lambda$. The spacings are $S = 0.25\ \lambda$, $0.375\ \lambda$, and $0.5\ \lambda$. As expected, the current distributions on the horizontal and the vertical wires exhibit sinusoidal forms with the same amplitude. Owing to the spacing S and the phase relation between the currents on the horizontal and the vertical wires, the backscattering waves for $S = 0.25\ \lambda$ and $S = 0.5\ \lambda$ are circularly polarized, while that for $S = 0.375\ \lambda$ is linearly polarized.

The axial ratio of the backscattering wave (on the z-axis) is shown in Fig. 3 as a function of the spacing S. Except for $S = 0.125\ n\lambda$ ($n = 0, 1, 2, \cdots$), the backscattering wave is elliptically polarized. In Fig. 3 the rotational sense of the backscattering wave is expressed by two curves: the dashed curve is for the right-handed sense; the solid curve for the left-handed

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The authors are with the Department of Electrical Engineering, College of Engineering, Hosei University, 3-7-2 Kajino-cho, Koganei City, Tokyo 184, Japan.

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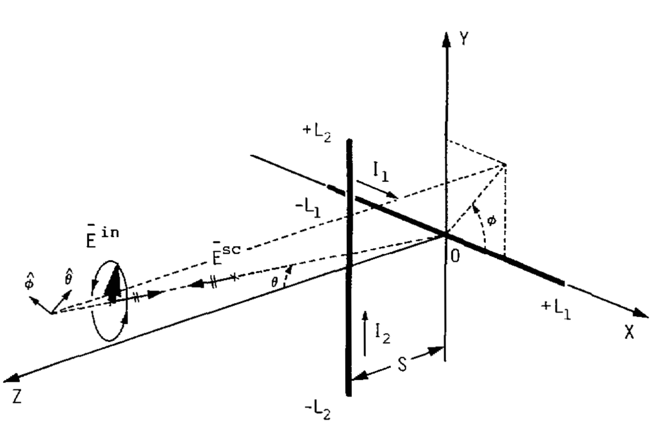

Fig. 1. Configuration of crossed-wire scatterer.

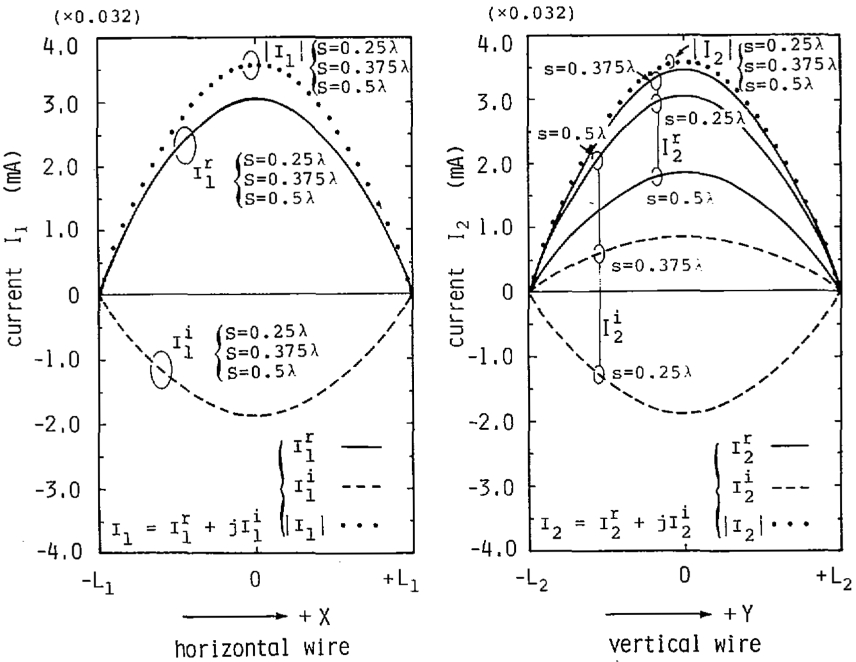

Fig. 2. Current distributions on horizontal and vertical wires as a function of spacing S:E_0 = 1 V/m. (Positive direction of current is in $+X$ or $+Y$ direction. The dashed curve for 0.5 λ on the vertical wire coincides with the solid curve for 0.25 λ.)

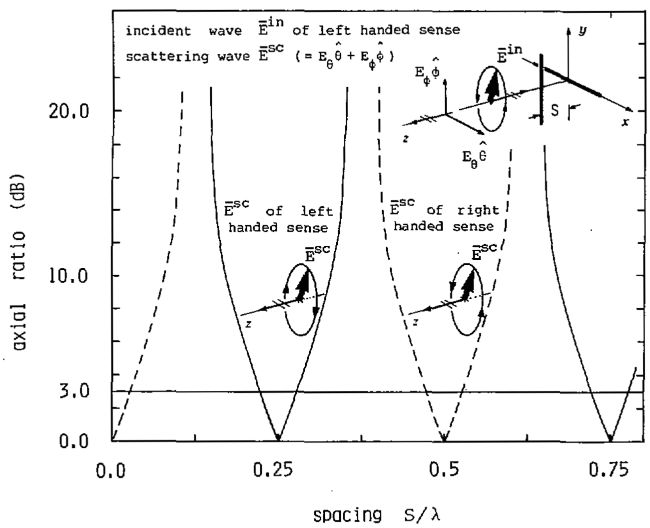

Fig. 3. Axial ratio observed in the normal direction as a function of spacing S. right-handed sense: ----; left-handed sense: ——.

sense. One should recall that the senses are determined by a relation between the directions of the rotation of electric field and the wave propagation. With either the right-handed sense or the left-handed sense, an axial ratio within 3 dB is repeated over the ranges of $S = 0.25\,n\lambda \pm 0.03\,\lambda$ $(n = 1, 2, \cdots)$.

The backscattering wave $\bar{E}^{sc}(=E_\theta\hat{\theta} + E_\phi\hat{\phi})$ is decomposed into two components which are circularly polarized with different intensities and rotational senses (left-handed sense and right-handed sense): $\bar{E}^{sc} = E_L(\hat{\theta} + j\hat{\phi}) + E_R(\hat{\theta} - j\hat{\phi})$. Using a relation of $|E_\theta|^2 + |E_\phi|^2 = (|E_L|^2 + |E_R|^2)/2$, the backscattering cross section σ is defined as

$$\sigma = \sigma_L + \sigma_R$$

where

$$\sigma_{i=L,R} = \lim_{r\to\infty} \frac{4\pi r^2 |E_i|^2}{|E_0|^2}$$

in which r is the distance from the scatterer to an observation point.

A backscattering wave which has the same rotational sense as an incident wave of circular polarization is called a "fundamental component," while a backscattering wave whose rotational sense is opposite to that of the incident wave is called a "cross component." In the present consideration the BSCS for the fundamental component is given by σ_L, since the incident wave is a circularly polarized wave of left-handed sense.

The cross component, which is regarded as single reflection in a planar metallic plate, is not detected in a CPW-radar, as mentioned in the Introduction. An important index as a radar cross section is given by the BSCS for the fundamental component. Fig. 4 shows that for the spacing $S = 0.25(2n + 1)\lambda(n = 0, 1, 2, \cdots)$ the BSCS for the fundamental component exhibits a maximum value of $0.64\ \lambda^2$.

So far, consideration has been given to the case where the incident wave $\bar{E}^{\text{in}}$ illuminates the scatterer from the z-axis direction. Fig. 5 shows the current distribution under the condition that the incident wave illuminates the scatterer from directions other than the z-axis. Although the current on the horizontal wire loses symmetry, the location of a maximum value of the current distribution remains near the middle point of each arm. For the angle of incidence $\theta = \pm 90^\circ$, the current is induced only on the vertical wire, and the backscattering wave is linearly polarized. This means that the BSCS for the fundamental component is half the total BSCS, or the cross component appears with the same intensity. Since the appearance of the cross component deteriorates the transformation efficiency of the incident energy to the fundamental component in the backscattering wave, it is desirable for the cross component to be as small as possible. Fig. 6 shows the BSCS's as a function of the angle of incidence θ. The difference in the BSCS between the fundamental and the cross components is 6 dB at the half-BSCS angle (angle at which the BSCS for the fundamental component is 3 dB down from the maximum value).

III. ARRAY OF STRAIGHT CROSSED-WIRE SCATTERERS

The enhancement of the BSCS is demonstrated in this section, using an array technique. Fig. 7 shows an array consisting of 2 X 2 straight crossed-wire scatterers. A circularly polarized wave of left-handed sense illuminates the array. The spacing S between the horizontal and the vertical wires is 0.25 λ so that the rotational sense of a backscattering wave from the array may be the same as that of the incident wave. The current distributions on the array elements are evaluated using the method of moment [9], as determined in Fig. 2 for a single crossed-wire scatterer. On the basis of the analyzed current distributions, the BSCS's are calculated.

First, the distance D between the array elements is determined in order to give a maximum value of the BSCS for the fundamental component, under the condition of the angle of incidence $\theta = 0^\circ$. Fig. 8 shows the BSCS for the fundamental component as a function of the distance D. It is found that at a distance of $D = 0.625\ \lambda$ the BSCS indicates a maximum value of $19.7\ \lambda^2$. The maximum BSCS of the array is about 31 times as large as that of the single crossed-wire scatterer shown in Fig. 4. This is attributed to the fact that, owing to the mutual effects among the array elements, the average value of the amplitudes of the currents on the array elements increases about 1.4 times as large as the amplitude shown in Fig. 2, i.e., a multiplicative factor is $(1.4 \times 4)^2 \cong 31$ for four elements.

Next, the BSCS is calculated as a function of the angle of

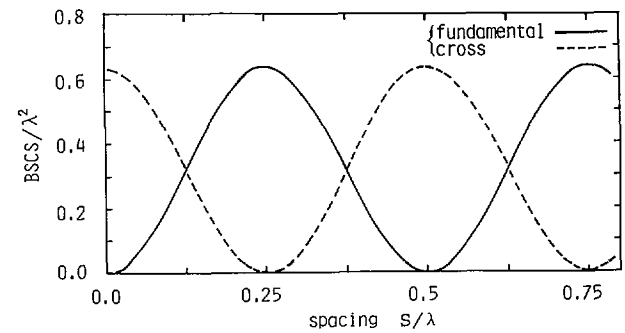

Fig. 4. Backscattering cross sections as a function of spacing S.

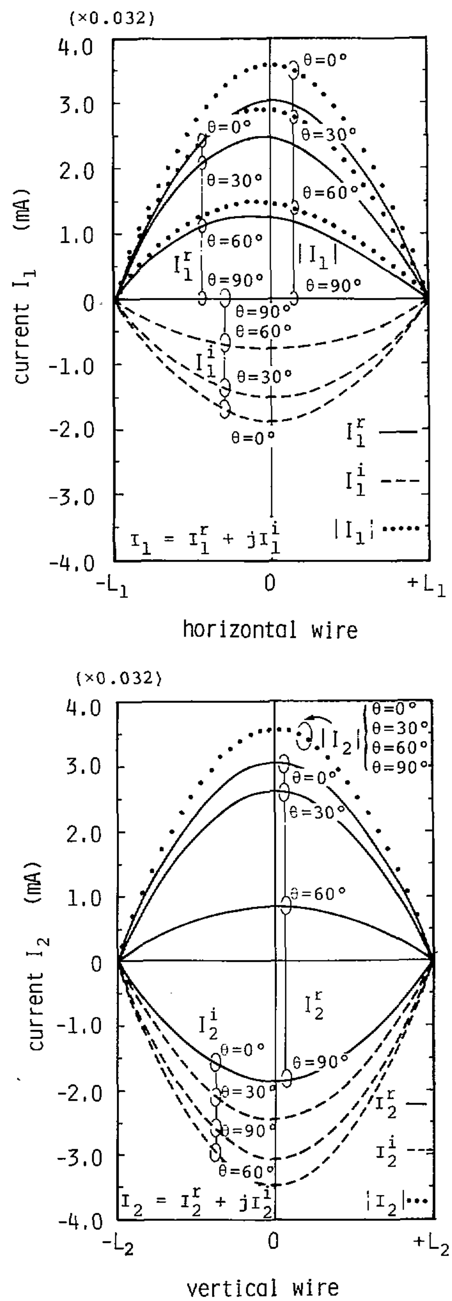

Fig. 5. Current distributions on straight crossed-wire scatterer as a function of angle of incidence θ: spacing $S = 0.25\ \lambda$; $E_0 = 1$ V/m.

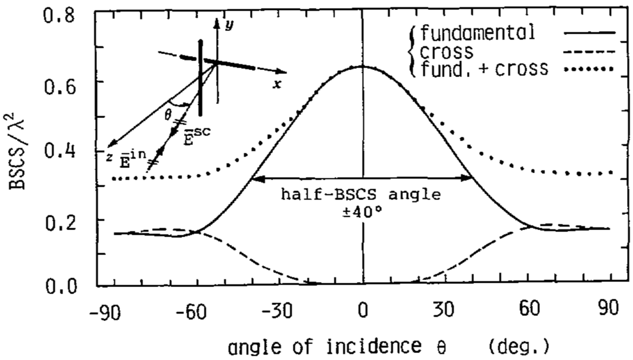

Fig. 6. Backscattering cross sections as a function of angle of incidence θ: $\phi = 0°$ plane (XZ-plane); spacing $S = 0.25\ \lambda$.

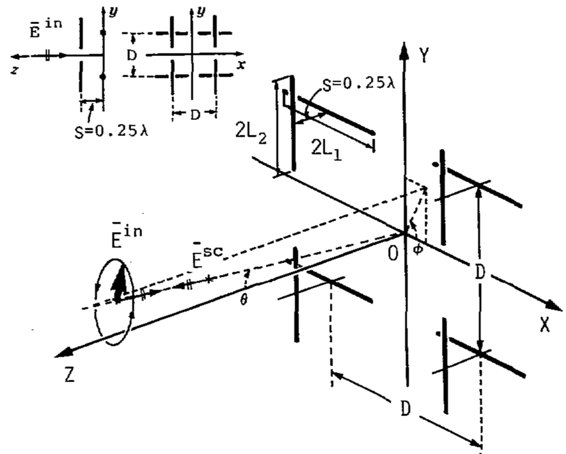

Fig. 7. Configuration of an array of 2 × 2 straight crossed-wire scatterers.

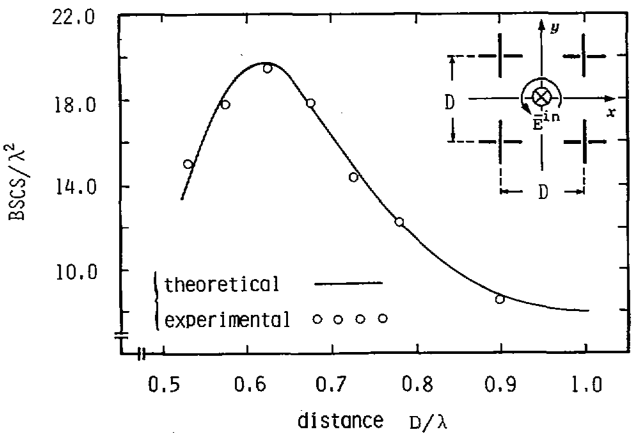

Fig. 8. Backscattering cross section for fundamental component as a function of distance D: spacing $S = 0.25\ \lambda$.

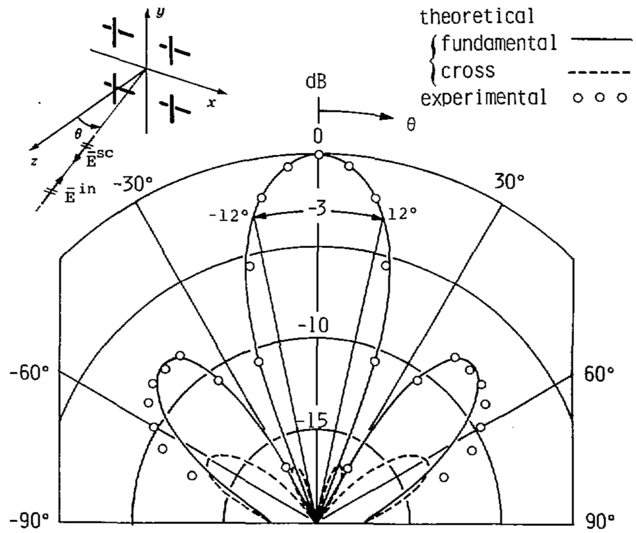

Fig. 9. Backscattering cross sections as a function of angle of incidence θ:$\phi = 0°$ plane; spacing $S = 0.25\ \lambda$; distance between elements $D = 0.625\ \lambda$; frequency $f = 9.375$ GHz.

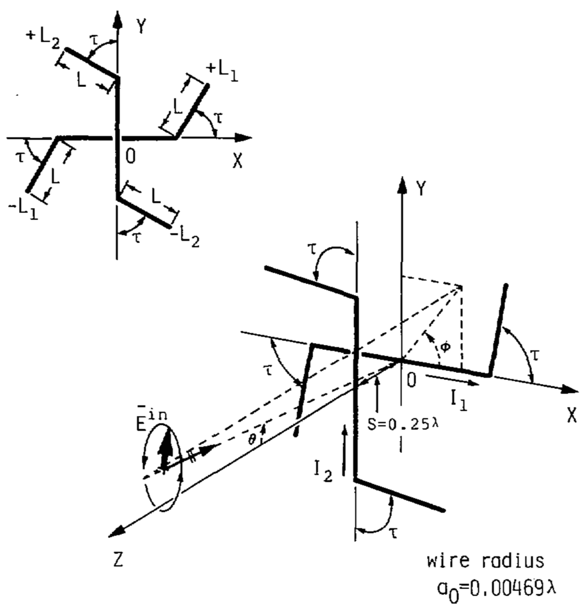

Fig. 10. Configuration of bent crossed-wire scatterer.

incidence θ. The distance between the array elements is fixed at $D = 0.625\ \lambda$. Fig. 9 presents numerical results with experimental results at a frequency of $f = 9.375$ GHz, showing good agreement between them. For auxiliary information, the BSCS for the cross component is also presented. The half-BSCS angle is $\pm 12°$, over which the BSCS for the cross component is smaller than -21 dB.

IV. BENT CROSSED-WIRE SCATTERER AND ITS ARRAYS

In the previous section the BSCS of an array consisting of straight crossed-wire scatterers has been calculated, and the increase in the BSCS has been demonstrated. In this section a bent crossed-wire scatterer is proposed to improve the radiation performance of the straight crossed-wire scatterer.

Fig. 10 shows the configuration of a single crossed-wire scatterer consisting of bent arms. The arm length is taken to be $2L_1 = 2L_2 = 0.5\ \lambda$, with a bend length of $L = 0.125\ \lambda$. The spacing S is chosen to be $0.25\ \lambda$ so as to produce a backscattering wave whose rotational sense is the same as that of an incident wave of circular polarization.

The idea of bending the arms comes from the fact found in a half-wavelength dipole antenna. The current amplitude of a half-wavelength dipole antenna bent at a middle point ($L = 0.125\ \lambda$) of each arm becomes a maximum value when a bend angle is about 90° [10]. The idea is applicable to a wire scatterer as a counterpart; when a half-wavelength isolated wire scatterer is illuminated by a linearly polarized wave, the current amplitude of the wire scatterer becomes a maximum value at a bend angle τ of about 90°, resulting in a maximum value

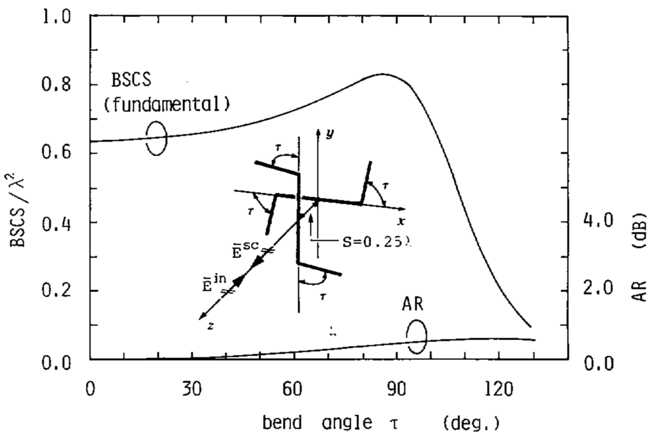

Fig. 11. Backscattering cross section for fundamental component and axial ratio as a function of bend angle τ.

of the BSCS. The described behavior of the current on the isolated wire scatterer also holds for an incident wave of circular polarization. It is noted that for the bend crossed-wire scatterer consisting of two arms as shown in Fig. 10, the bent angle should be determined so that the BSCS may be a maximum value, taking the mutual coupling between the arms into account.

Fig. 11 shows the BSCS for the fundamental component and the axial ratio as a function of bend angle τ. The calculations are carried out under the condition that an incident wave of circular polarization of left-handed sense illuminates the bent crossed-wire scatterer from the angle of incidence $\theta = 0^\circ$. The excellent axial ratio leads to an extremely small BSCS for the cross component with consequent disappearance in Fig. 11. It is found that the BSCS for the fundamental component exhibits a maximum value of 0.826 λ^2 at a bend angle of about 85° with almost entirely circular polarization, and that the maximum value increases about 30 percent above the BSCS for $\tau = 0^\circ$ (straight-arm crossed-wire scatterer). The favorable increase in the BSCS results from the enhancement in the current amplitudes, as shown in Fig. 12. Although increasing the current amplitudes can be realized by an alternative way of truncating the wires slightly, bending the wires has an advantage that an aperture area for $\tau = 85^\circ$ is only 30 percent of that for $\tau = 0^\circ$.

Fig. 13 shows the BSCS's of the bent crossed-wire scatterer with $\tau = 85^\circ$ as a function of the angle of incidence θ. Comparing Fig. 13 with Fig. 6, one observes that the BSCS for the fundamental component of the bent crossed-wire scatterer increases near the z-axis, while the BSCS for the cross component remains almost the same as that of the straight crossed-wire scatterer. Hence, a relative intensity of the fundamental component to an intensity of the cross component increases near the z-axis. The difference in the BSCS between the fundamental and the cross components at the half-BSCS angle improves to 7 dB from 6 dB for the straight crossed-wire scatterer. Further improvement will be found in an array consisting of the bent crossed-wire scatterers.

On the basis of the results mentioned above, an array is constructed using 2 × 2 bent crossed-wire scatterers with the bend angle of $\tau = 85^\circ$. Fig. 14 shows the BSCS and the axial ratio of the array as a function of the distance D between the elements. A maximum value of the BSCS for the fundamental component, 28.5 λ^2, is obtained at a distance of $D = 0.69\ \lambda$, where the array radiates a circularly polarized wave with an axial ratio of 0.36 dB. The axial ratio corresponds to a BSCS for

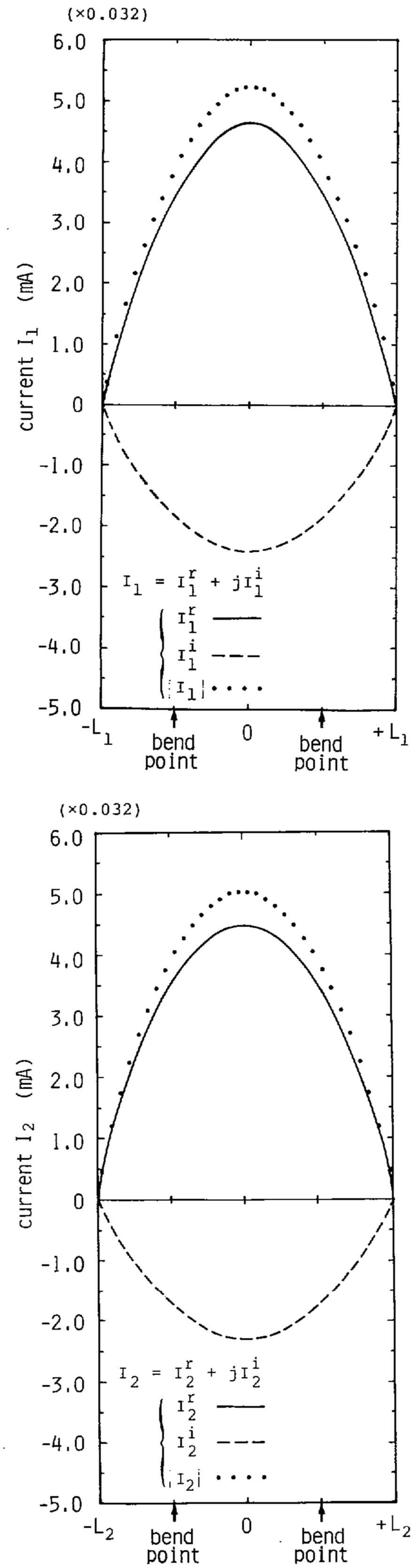

Fig. 12. Current distributions on bent crossed-wire scatterer: bend angle $\tau = 85°$; spacing $S = 0.25\ \lambda$; $E_0 = 1$ V/m.

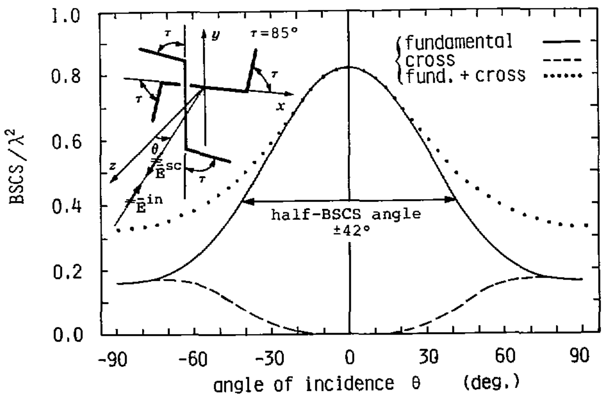

Fig. 13. Backscattering cross sections as a function of angle of incidence θ: $\phi = 0°$ plane; spacing $S = 0.25\ \lambda$.

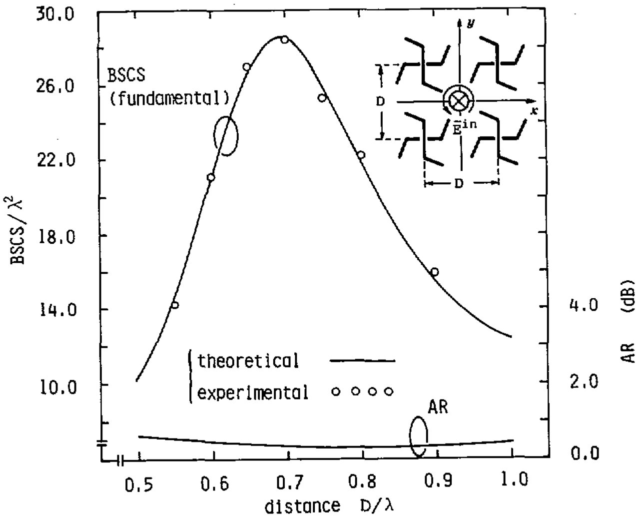

Fig. 14. Backscattering cross section for fundamental component as a function of distance D: bend angle $\tau = 85°$; spacing $S = 0.25\ \lambda$.

the cross component of $0.012\ \lambda^2$. This value is only 0.04 percent of the BSCS for the fundamental component and is not appreciable in Fig. 14.

Fig. 15 shows the BSCS's of the array as a function of the angle of incidence θ. The half-BSCS angle is $\pm 11°$. The difference in the BSCS between the fundamental and the cross components at the half-BSCS angle improves to 23 dB from 18 dB for the array of the straight crossed-wire scatterers shown in Fig. 9.

Subsequently, investigation is made about an array consisting of 3 X 3 elements with the bend angle of $\tau = 85°$. Fig. 16 shows the current amplitudes of the array elements separated at a distance of $D = 0.745\ \lambda$, where the BSCS for the fundamental component becomes a maximum value of $213\ \lambda^2$. The maximum BSCS of the array is about 258 times as large as that of the single bent crossed-wire scatterer shown in Fig. 11. The average of the current amplitudes of the array is about 1.8 times as large as that of the single bent crossed-wire scatterer, due to the mutual effects among the array elements. An approximate calculation of $(1.8 \times 9)^2$ for nine array elements accounts for a multiplicative factor of 258. It is also confirmed that, as the distance D between the array elements is increased, a maximum value of the BSCS for the fundamental component approaches a value which is $81[=(3 \times 3)^2]$ times as large as that of the single bent crossed-wire scatterer.

A comparison between the array and a dihedral corner reflector shows that the maximum BSCS of the former is about 1.8 times as large as that of the latter, both having the same aperture area. A comparison between them also indicates that the array structure has an advantage in that the spacing S is independent of an increase of the aperture area, i.e., $S = 0.25\ \lambda$. On the other hand, the dihedral corner reflector is forced to occupy a deeper spacing between the aperture plane and the intersection of the two metallic planes, increasing the aperture area.

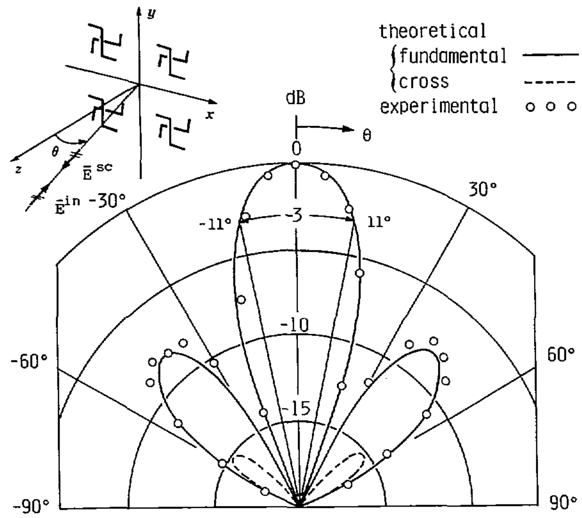

Fig. 15. Backscattering cross sections as a function of angle of incidence θ: $\phi = 0°$ plane; bend angle $\tau = 85°$; spacing $S = 0.25\ \lambda$; distance between elements $D = 0.69\ \lambda$.

Fig. 17 shows the BSCS as a function of the angle of incidence θ. The half-BSCS angle is $\pm 6.5°$, over which the BSCS for the cross component is less than -31 dB and is not appreciable in Fig. 17.

V. CONCLUSION

A straight crossed-wire scatterer without a junction point and arrays of them have been discussed from an aspect of producing a backscattering wave whose rotational sense is the same as that of an incident wave of circular polarization. Based on the characteristics of the straight crossed-wire scatterer, an array consisting of 2 X 2 elements is constructed. It is found that the mutual effects among the array elements lead to the increase in the amplitudes of the currents on the array elements, with consequent enhancement of the backscattering cross section.

In order the improve the radiation performance of the straight crossed-wire scatterer, a bent crossed-wire scatterer is proposed. Bending the wires contributes to increasing the BSCS for the fundamental component, so that the difference in the BSCS between the fundamental and the cross components becomes large. For an array of 2 X 2 bent crossed-wire scatterers with a bending angle of 85°, the difference in the BSCS between the fundamental and cross components at the half-BSCS angle improves to 23 dB from 18 dB for the straight-wire scatterers.

For better understanding of the performance on the array consisting of bent crossed-wire scatterers, an array of 3 X 3 elements is constructed. The BSCS for the fundamental component exhibits a maximum value of $213\ \lambda^2$ with a half-BSCS angle of $\pm 6.5°$. It is worth mentioning that the maximum BSCS of the array is 1.8 times as large as that of a dihedral corner reflector with the same aperture area. Numerical results of the BSCS as a function of the angle of incidence agrees well with experimental ones.

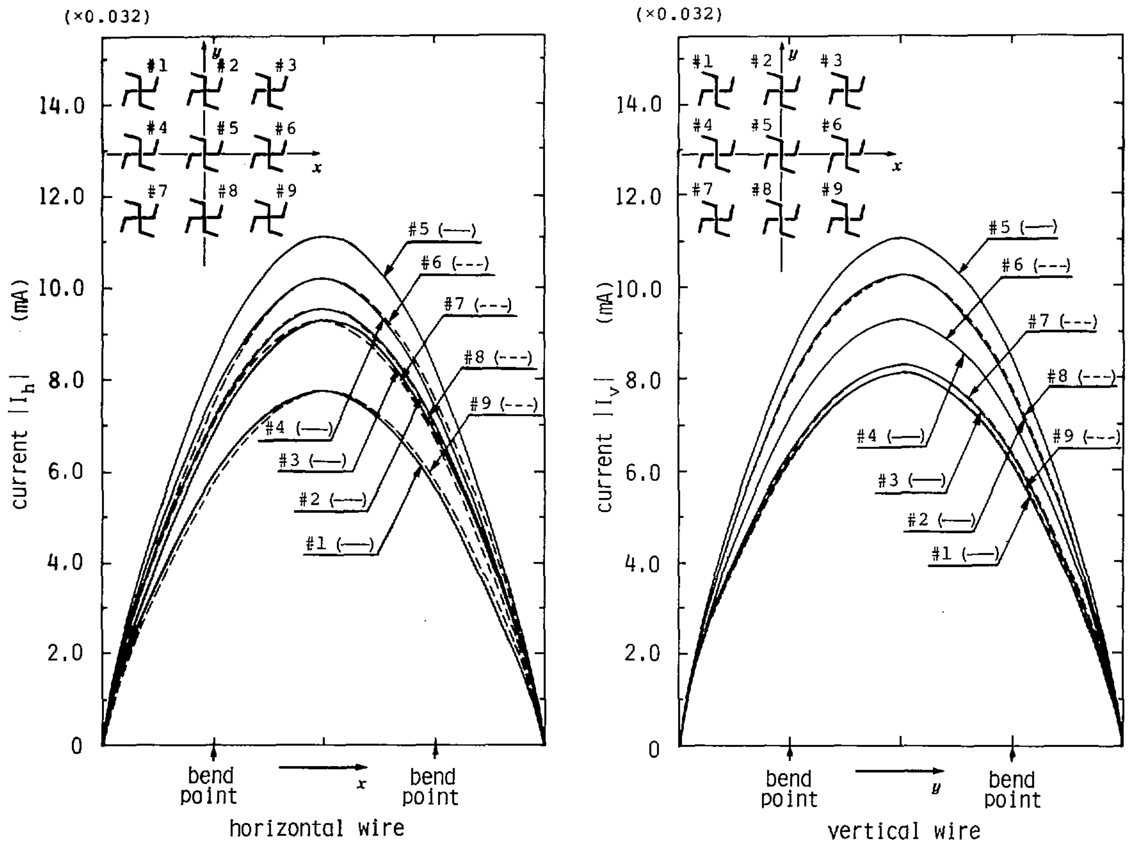

Fig. 16. Current amplitudes on 3 × 3 bent crossed-wire scatterers: bend angle $\tau = 85°$; spacing $S = 0.25\ \lambda$; distance between elements $D = 0.745\ \lambda$; $E_0 = 1$ V/m.

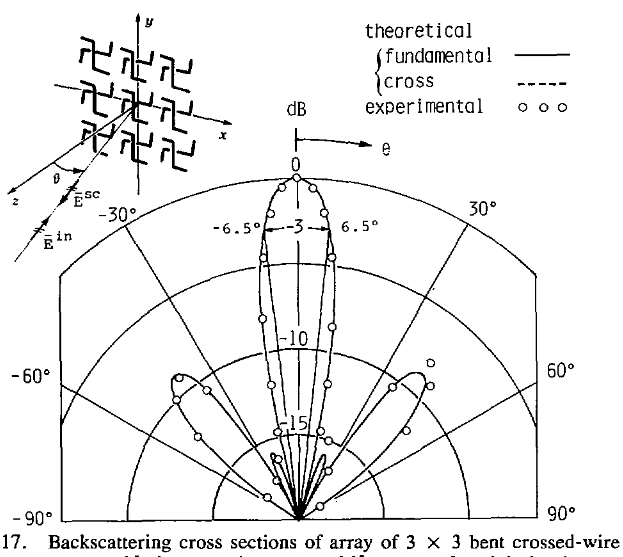

Fig. 17. Backscattering cross sections of array of 3 × 3 bent crossed-wire scatterers: $\phi = 0°$ plane; bend angle $\tau = 85°$; spacing $S = 0.25\ \lambda$; distance between elements $D = 0.745\ \lambda$.

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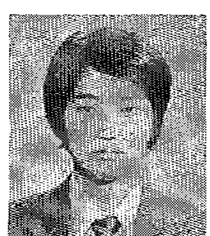
Hisamatsu Nakano (M'75), for a photograph and biography please see page 840 of the August 1984 issue of this TRANSACTIONS.



Akihiro Yoshizawa was born in Tokyo, Japan, on November 24, 1960. He received the B.E. and M.E. degrees in electrical engineering from Hosei University, in 1983 and 1985, respectively.

He was engaged in the design of microwave antennas. He joined the Matsushita Electric Industrial Co. Ltd., Osaka, in 1985.

Mr. Yoshizawa is a member of the Institute of Electronics and Communication Engineers of Japan.

Junji Yamauchi, for a photograph and biography please see page 840 of the August 1984 issue of this TRANSACTIONS.