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Planar Passive Electromagnetic Deflector for Millimeter-Wave Frequencies

M. C. T. Kastelijns, *Student Member, IEEE*, and J. A. G. Akkermans, *Student Member, IEEE*

Abstract—A novel passive planar structure is proposed that is able to deflect an incoming electromagnetic (EM) wave into a desired direction. The direction of the outgoing EM wave is determined by the design of this deflector. The deflector can be used to extend coverage of a steerable source with limited scan capabilities. It consists of elements which alter the phase distribution of the incoming EM wave. It is called deflector, because it is designed primarily to deflect incoming EM waves, as opposed to focusing as in the case of the array lens. The design of a compact phase-shifting deflector element is given. Two deflectors have been designed and constructed. Measurements show good agreement with simulations.

Index Terms—Beam steering, deflector, extended coverage, electromagnetic (EM) refraction, millimeter wave antennas.

I. INTRODUCTION

THE coverage of a single planar antenna array is typically limited, because it exhibits low directivity at scan angles far from broadside. To extend the coverage, multiple antenna arrays can be placed on a 3-D structure, but this requires an extensive feed configuration, which is difficult to realize. To overcome this problem, a reflectarray [1] can be used in combination with a fixed source. This source is placed above the reflectarray, thereby causing shadowing. Alternatively, the authors propose a configuration where the source is located behind a novel planar passive deflecting array, called a deflector. Multiple deflectors can be used to form a 3-D structure, as shown in Fig. 1. The deflector is able to extend coverage of a steerable source with limited scan capabilities. Key feature of the deflector is the ability to deflect, i.e., bend, waves while they pass through. Depending on which area the incident wave is focused on, the deflector bends this wave towards a new direction, possibly out of reach of the source itself. Additionally, an incident wave can be focused towards the new direction.

The application of interest is communication in the 60-GHz band. In this license-free band, data rates in the order of gigabits per second are feasible. Because of the high free-space loss, this band is very suitable for indoor communication, but also requires beamforming antennas with large scan range and sufficient gain.

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The authors are with the Radio Communications Group (ECR), Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven 5600, The Netherlands (e-mail: M.C.T.Kastelijns@student.tue.nl; J.A.G.Akkermans@tue.nl).

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Fig. 1. Proposed configuration.

The elements of a deflector are similar to those of a reflectarray, in the sense that they are designed to receive an incident wave and apply the necessary phase shifts to form a wave towards a specified direction. These phase shifts may be achieved by varying length stubs [2]–[4], but stubs produce dissipative losses and spurious radiation. Another way to achieve varying phase shifts is to use patches of variable sizes [5], [6] or even elements with variable rotation angles [7], but these methods are limited in bandwidth. The bandwidth can be improved by using multiple layers, as suggested in [8]. As opposed to a reflectarray, the deflector needs to receive an incident wave on one side and reemit this wave on the other side. Such a structure is also presented in [9], where the design of a planar lens is discussed. This design is capable of focusing an incident wave by performing phase shifts at a frequency of 8 GHz. This planar lens is similar to the proposed design in the sense that they are both constructed of passive, transmissive elements, which use transmission lines of varying length to apply an appropriate phase shift. The proposed design extends this design. Most important difference is the fact that the proposed design uses four metal layers, is capable of deflecting waves into a new direction, and achieves good transmission at millimeter-wave frequencies, which, to our knowledge, has not been presented in literature before.

II. DEFLECTOR ELEMENT

The deflector element is based on the design described in [10], where an antenna consisting of a patch, two coupling apertures, and a reflector is discussed. Here, a wideband design is obtained by using both the patch and the coupling apertures as resonant elements. The antenna achieves good efficiency, because the coupling apertures partly cancel the surface waves that are launched in the substrate. A good front-to-back ratio is obtained by incorporating the reflector.

The initial design of the deflector element is based on the combination of two such antenna elements. One element receives at one side and the other element emits to the other side,

Fig. 2. Deflector element: (a) stack and (b) initial design.

Fig. 3. Final design of the deflector element.

with a balanced transmission line in between to apply an appropriate phase shift (Fig. 2). The two separate elements can be combined to obtain a compact design, as shown in Fig. 3. One element is rotated by 90° and the patch and the reflector of both elements are combined. To achieve this, the patch of one side is enlarged in one direction to act as the reflector for the other side. In the resulting design, the polarization of the emitted wave is orthogonal to the polarization of the incident wave.

The element is modeled with CST Microwave Studio, a full-wave EM simulator. Three different elements are designed (Fig. 4), which realize a phase shift of -120° , 0° , and 120° at a frequency of 60 GHz. The size of the elements is $3.2 \text{ mm} \times 3.0 \text{ mm}$, which corresponds to 0.64×0.60 times the wavelength at 60 GHz. Simulation results of the element show good transmission properties for the frequency range of 57–63 GHz, which is a 10% bandwidth within the 60-GHz band.

III. SIMULATION AND MEASUREMENT RESULTS

A deflector is constructed by placing multiple deflector elements in a regular pattern. The three elements shown in Fig. 4 are placed in an alternating order along one direction. Along the other direction, the elements are identical. In this way, a deflector is obtained, which deflects an incident plane wave by 34° .

Fig. 4. Deflector elements: (a) -120° , (b) 0° , and (c) 120° .

Fig. 5. Normalized gain of 0° deflector (deflecting plane, $f = 60 \text{ GHz}$); measured (—); simulated (---).

The transmission properties of this 34° deflector is compared to a second, 0° deflector, which is constructed out of identical elements. This deflector does not change the phase distribution, and therefore, the outgoing wave propagates in the same direction as the incident wave. Both deflectors are realized in a stack consisting of four metal layers with dielectric material in between, as shown in Fig. 2(a). The upper and the lower dielectric have a thickness of 0.254 mm and a permittivity of 2.17. The middle dielectric has a thickness of 0.112 mm and a permittivity of 2.6. Both deflectors are constructed of 9×9 elements. The dimensions of the deflectors are $28.8 \text{ mm} \times 27.0 \text{ mm}$.

The deflectors are excited by a conical horn. The radius of the horn aperture is 11.0 mm. An HP/Agilent E8361A PNA network analyzer is used for S-parameter measurement up to a frequency of 67 GHz. To measure the radiation pattern, a custom-built measurement setup is used, able to measure the far-field radiation pattern of the deflectors [11]. Averaging is used to limit the influence of noise and time gating is applied to remove the influence of reflections from the environment. Due to space limitations of the measurement setup, the horn is placed 13 mm away from the deflector. The deflector is, therefore, not in the far-field region of the horn. Absorbing material is placed around the deflector to prevent spurious radiation from the horn from passing the deflector at the sides and thereby disturbing the radiation pattern of the deflector. Figs. 5 and 6 show the normalized radiation patterns for both deflectors in the deflecting plane at a frequency of 60 GHz. Fairly good agreement between measured and simulated results is obtained in Fig. 5 and good agreement is ob-

Fig. 6. Normalized gain of 34° deflector (deflecting plane, $f = 60$ GHz); measured (—); simulated (--).

Fig. 7. Measured normalized gain of both deflectors; 0° deflector (—); 34° deflector (--).

tained in Fig. 6. Sidelobe levels are in the order of -10 dB. The difference between sidelobe levels of measured and simulated results in Fig. 5 can be explained by the fact that the absorbing material, used in the measurements, is not included in the simulations. Fig. 7 shows the normalized gain for both deflectors as a function of frequency, measured at their peak angles of $\theta = 0^\circ$ and $\theta = 34^\circ$, respectively. The 0° deflector shows best performance for a frequency of 56 and 62 GHz and the 34° deflector shows best performance for a frequency of 59 and 62 GHz. The transmission of the 0° deflector as a function of frequency is slightly better than that of the 34° deflector.

IV. CONCLUSION

A novel passive planar structure, called a deflector, has been proposed, which is able to deflect an incoming EM wave towards a desired direction. It has been explained that an antenna configuration incorporating a deflector is able to achieve extended coverage without the use of difficult interconnections. A possible design of the deflector element has been proposed and simulations show good transmission properties for a bandwidth of 10% within the 60-GHz band. Two deflectors have been constructed, one of which is able to deflect incident waves by 34° . Measured and simulated results show good agreement. Sidelobe levels are in the order of -10 dB. The measurements confirm the ability of the deflector to deflect waves into another direction.

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