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SUPER-RESOLVING BIOMIMETIC ELECTRICALLY SMALL ANTENNAS AND THEIR APPLICATIONS

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ABSTRACT: **Many small animals possess acute directional hearing capabilities and are able to localize a sound source of interest with an astonishing degree of precision. An analogy can be drawn between the hearing mechanisms of these small animals and electrically small antenna arrays, composed of isotropic receiving elements, that are capable of resolving the direction of arrival of an electromagnetic wave with a fine angular resolution. Inspired by this analogy between these acoustical biological devices and electrically small antenna arrays, we introduce the concept of biomimetic, super-resolving electrically small antennas in this paper. The paper also describes potential applications of these devices and the new capabilities that they offer. A method for designing such electrically small antenna arrays as well as simulated and measured results of a fabricated prototype are also resented and discussed in this paper. These biomimetic antenna arrays could be used in numerous applications ranging from miniaturized RF sensors and direction finding systems to small aperture, high-resolution microwave imaging systems and radars.**

1. INTRODUCTION

Electrically small antennas have been the subject of many studies over the past few decades. In particular, a number of theoretical studies have examined the relationship between the electrical dimensions (physical dimensions normalized to the wavelength) of an antenna and its radiation characteristics including gain, radiation efficiency, bandwidth, and directional characteristics [1-9]. All of these studies point to a set of either *fundamental* or *practical limitations* that govern the performance of such antennas. In particular, as the electrical dimensions of an antenna are decreased, its radiation efficiency and bandwidth also decrease [1-3]. These studies propose a set of *fundamental limits* that predict the upper bounds of these radiation parameters as demonstrated by the famous Chu limit [1] and its subsequent variations. Similar theoretical studies have been carried out to investigate the relationship between the directionality of an antenna array or continuous aperture [3-9] and its electrical size. The results show that, in theory, achieving superdirectivity is possible from an antenna array or a continuous aperture. In principle, such super-directive arrays could be used to precisely resolve the direction of arrival of an EM wave. In this regard, a super-directive antenna array composed of isotropic receiving elements can be used to resolve the direction of arrival of an electromagnetic (EM) wave. However, when the overall electrical dimensions of the antenna array decrease, the nearby elements of the array must be excited with significantly oscillatory and widely varying excitation coefficients to achieve super-directional characteristics [8, 9]. While mathematically possible, the realization of such excitation coefficients is not practical for small antenna arrays due to problems such as mutual coupling between the elements and tolerances in device design and fabrication. This presents a set of *practical limitations* in the path of using highly-directional, electrically small antennas to obtain super-resolving capabilities. While we have not yet been able to overcome these problems, nature provides us with examples of biological organisms that have addressed similar problems.

The biological organisms' ability to evolve in response to environmental changes and the hyperacute sensing capabilities that some organisms have evolved point to an interesting question: *How would a biological entity evolve the capability to receive and transmit electromagnetic waves if an evolutionary environment was present in which it would have needed this capability to survive?* The answer to this question could reveal new methodologies and concepts for designing small antenna systems that work within the bounds set by the laws of physics but deliver performance levels that have not been achieved to date. A good starting point for answering this question is to investigate biological organisms that already possess similar capabilities. Among a plethora of organisms that could be studied, insects are the most magnificent and inspiring subjects, since many insect species have hyperacute and extremely efficient sensing capabilities in ultra-small packages. In particular, the sense of directional hearing in certain insect species [10-14] and small vertebrates [15-17] is most germane to the problem of super-resolving electrically small antenna arrays. Many animals use sound waves for communication and sensing. The auditory system of such creatures have evolved and adapted to be able to detect the sound waves of interest and identify and localize their sources. To achieve this, most animals use two ears, which act as pressure sensitive receivers excited by the pressure of an incoming sound wave. Based on its direction of incidence, the sound wave arrives at one ear earlier than the other. Additionally, the amplitude of the vibrations at the two ears are generally different due to the scattering caused by the animal's body. These differences in the time of arrival and the amplitude of the two received signals are the main cues used by the auditory system of most animals to determine the location of the emitting source. In large animals and humans, the separation between the two ears is physically large and significant scattering of sound is created by the large head separating the two ears. This results in large interaural time differences (ITDs) and interaural intensity differences (IIDs) between the two received signals that can be easily detected by the animal's central nervous system. As the size of the animals decrease, however, these differences become smaller and smaller. Therefore, one would think that smaller animals and especially insects are inherently at a disadvantage when it comes to directional hearing. However, surprisingly, many small animals demonstrate hyperacute directional hearing capabilities. In the insect world, various species of cicadas [10], crickets [11], parasitoid flies [12-13], and grasshoppers have acute directional hearing capabilities. Similar characteristics are also found among small vertebrates in various species of frogs [15-16], reptiles [17], and birds [18]. In all of these examples, the auditory organ of the animal is composed of two ears separated by a very small distance from each other (compared to the wavelength of sound). Due to this small separation and the small size of the animals' heads (or insects' bodies), there is little or no intensity difference between the level of sound that arrives at the two ears. Therefore, the only cues available are the small differences in the time of arrival of the sound between the two ears. The auditory systems of these organisms amplify these minute differences in the time of arrival of sound and increase them to detectable levels. In this paper, we will demonstrate how the sense of directional hearing in insects can be used to develop super-resolving electrically small antennas and present preliminary results of these biomimetic antennas and discuss the potential applications of the proposed biomimetic antenna arrays.

Fig. 1. Photograph of the parasitoid fly *Ormia Ochracea*. The fly has two ears that are separated from one another by 500 μm. The entire body length of the fly is almost 1 cm long. Photo courtesy of Prof. William H. Cade from University of Lethbridge, Lethbridge AB, Canada. Used with permission.

2. BACKGROUND AND THE PROPOSED CONCEPT

An example of an insect which possesses an astonishing directional hearing capability is the parasitoid fly *Ormia Ochracea* shown in Fig. 1. Female *Ormia Ochracea* flies rely on live field crickets to reproduce [12]. They locate their hosts at night relying only on auditory cues from the male crickets' mating calls, which have peaks at 4.8 kHz with a free space sound wavelength, λ_{s0}, of 7 cm. The separation between the two ears of the fly is approximately 500 μm or equivalently $\lambda_{s0}/140$. Additionally, the fly's body size of 1 cm is significantly smaller than the wavelength and does not cause considerable scattering of the sound wave. Yet the fly is capable of discriminating the direction of arrival of the cricket's mating call with a precision of 1°-2° [14]. The details of the auditory organ of this insect have been analyzed in a number of publications. It has been demonstrated that the amazing directional hearing capabilities of this and other small animals are in part due to the presence of a set of coupled ears, which act as pressure difference receivers [19-20]. This is in sharp contrast to larger animals and humans that have isolated ears acting as pressure receivers. In *Ormia Ochracea* the separation between the two ears is so small that they are physically connected together using a flexible mechanical lever as shown in Fig. 2. This coupled ear mechanism enhances the

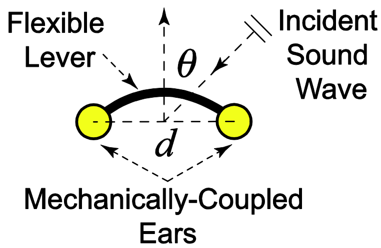


Fig. 2. Schematic of the mechanically-coupled ears of *Ormia Ochracea*. The hearing system of this fly consist of two tympanal membranes located within 500 µm of each other and connected together using a flexible mechanical lever.

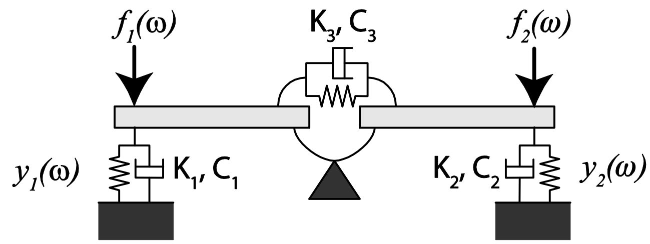


Fig. 3. Mechanical system modeling the performance of the *Ormia Ochracea's* hearing mechanism [19]. This model is shown to predict the measured frequency response of *Ormia Ochracea's* hearing mechanism with a reasonable degree of accuracy [19].

minute difference in the time of arrival of the sound wave between the two ears and amplifies it to a level that is detectable by the fly's simple nervous system.

Various mechanical models for the coupled ears of small animals have been proposed over the years. A simplified mechanical model of the fly's ear, proposed in [19], is shown in Fig. 3. This model is shown to be capable of predicting the measured frequency response of the fly's ear with a reasonable degree of accuracy [19]. A close examination of this model reveals that this is a second-order coupled resonator mechanical system with two inputs, $f_1(\omega)$ and $f_2(\omega)$, and two outputs, $y_1(\omega)$ and $y_2(\omega)$. They respectively represent the forces exerted on each tympanal membrane and the vibration amplitudes of each tympanal membrane. We can use the equivalency between the basic mechanical elements (mass, damper, and spring) and electrical circuit elements (inductor, capacitor, resistor) to derive two *electrical* equivalent circuit models of *Ormia Ochracea's* ear as shown in Fig. 4. Fig. 4(a) shows a second-order coupled resonator network with two inputs, $v_1(\omega)$ and $v_2(\omega)$, and two outputs, $i_1(\omega)$ and $i_2(\omega)$. Fig. 4(b) shows the dual of this circuit, which is also a coupled-resonator circuit with two inputs, $i_1(\omega)$ and $i_2(\omega)$, and two outputs $v_1(\omega)$ and $v_2(\omega)$. Since the two inputs of these circuits represent the input signals at each ear, under sinusoidal excitation, they will have the same magnitude and only a small phase difference between them caused by the difference in time of arrival of sound between the two ears. This phase difference can be expressed as $\Phi_{\text{in}}(\theta) = 2\pi d \sin\theta / \lambda_{s0}$, where $d \ll \lambda_{s0}$ is the spacing between the two ears, and θ is the incidence angle (see Fig. 2). Analysis of this circuit reveals that by properly choosing the element values (R_1, L_1, C_1, ...), it can be designed to increase the phase difference between the two output signals, even though the two input signals are almost identical. Assuming that the two inputs are represented as $v_1 = 1$ and $v_2 = e^{-j\Phi_{\text{in}}(\theta)}$, the outputs can be represented as $i_1 = A(\theta)e^{j\phi_1(\theta)}$ and $i_2 = B(\theta)e^{j\phi_2(\theta)}$, where $A(\theta)$ and $B(\theta)$ represent the output amplitudes and $\phi_1(\theta)$ and $\phi_2(\theta)$ represent their phases. We define the output phase difference as $\Phi_{\text{out}}(\theta) = \phi_1(\theta) - \phi_2(\theta)$. *Ormia Ochracea's*

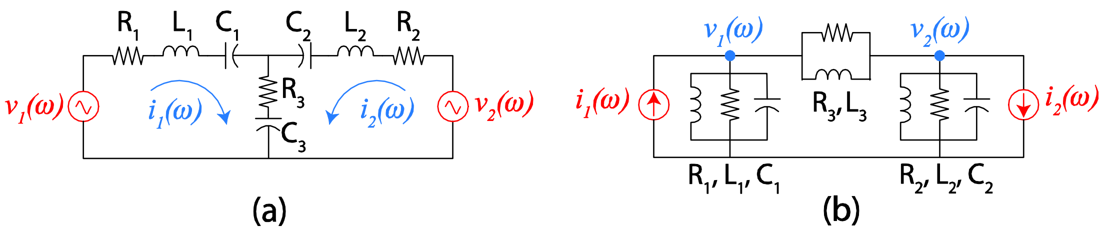


Fig. 4. The equivalent circuit models for the ear of parasitoid fly *Ormia Ochracea.* The circuit model of part (a) is obtained when considering force in a mechanical system to be analogous to voltage in an electric circuit and velocity to current. The dual of this circuit depicted in part (b) is obtained when choosing force to be analogous to current and velocity to voltage.

mechanically coupled ears significantly increase the output phase difference $\Phi_{\text{out}}(\theta)$ with respect to $\Phi_{\text{in}}(\theta)$ over a frequency range containing the peak intensity of the male cricket's mating calls. This allows the fly to precisely determine the direction of arrival of the incoming sound and localize the location of its host.

3. BIOMIMETIC ELECTRICALLY SMALL ANTENNAS

We can draw an analogy between the hearing mechanism of *Ormia Ochracea* and a simple two element antenna array. Figure 5 shows the comparison between a regular two-element antenna array and a biomimetic antenna array (BMAA) based on *Ormia Ochracea's* hearing mechanism. Assuming that the two elements of the array are separated by a distance of $d \ll \lambda_0$ (λ_0 is the free space wavelength of the EM wave) and the array is illuminated with an incident plane EM wave, the outputs of the two antenna elements of the regular array will have the same magnitude and a phase difference of $\Phi_{\text{in}}(\theta) = kd\sin\theta$, $k = 2\pi/\lambda_0$. On the other hand, in a properly designed BMAA, the phase difference between two outputs, $\Phi_{\text{out}}(\theta)$, can be significantly larger than $\Phi_{\text{in}}(\theta)$. To quantify this, we can define a dimensionless quantity called Sensitivity Factor (SF) for the two antenna arrays as:

$$SF_{RA}(\theta) = |1 + x_1/x_2|^2 = \left|1 + e^{-j\Phi_{\text{in}}(\theta)}\right|^2 \quad (1)$$

$$SF_{BMAA}(\theta) = |1 + y_1/y_2|^2 = \left|1 + A(\theta)/B(\theta)e^{-j\Phi_{\text{out}}(\theta)}\right|^2 \quad (2)$$

where SF_{RA} and SF_{BMAA} refer respectively to the sensitivity factors of the regular array and that of the BMAA. The angular variations of sensitivity factor are henceforth referred to as the sensitivity pattern. The sensitivity pattern is a dimensionless quantity, which can be used as a measure for quantifying the capability of a receiving array, composed of two closely spaced isotropic antennas, in determining the direction of arrival of an incoming EM wave. For the BMAA, this sensitivity factor is in fact the ratio of the power of two signals, $y_1(\theta) + y_2(\theta)$ and $y_2(\theta)$, i.e.:

$$SF_{BMAA}(\theta)|_{dB} = 10\log(|y_1 + y_2|^2/|y_2|^2) \tag{3}$$

where $y_1(\theta)$ and $y_2(\theta)$ are the outputs of the BMAA circuit shown in Fig. 5(b). Therefore, its value can be determined using two simple power measurements. The sensitivity pattern is different from the traditional array factor, which is an indication of the amount of power received by the array. For the regular array shown in Fig. 5(a), the sensitivity pattern and the normalized array factor have the same angular dependency. On the other hand, as will be shown later, the angular variations of the sensitivity pattern of the BMAA are considerably different from those of its array factor. Comparison of (1) and (2) reveals that if $\Phi_{\text{out}}(\theta)$ can be approximated as a linear function of $\Phi_{\text{in}}(\theta)$ with a slope of $m > 1$, then the sensitivity pattern of the two-element biomimetic array is equivalent to that of a regular two-element array with a spacing of $m \times d$ between the two elements. In other words, as far as spatial resolving capabilities of a receiving array are concerned, the effective aperture size of the two-element biomimetic array is m times its maximum physical size, d. However, as is shown below, due to the nonlinear relationship between $\Phi_{\text{out}}(\theta)$ and $\Phi_{\text{in}}(\theta)$, this virtual aperture amplification is even more significant allowing a simple two-element BMAA to have a sensitivity pattern equivalent to a multi-element array with significantly larger aperture dimensions and half-wavelength spacing between the elements.

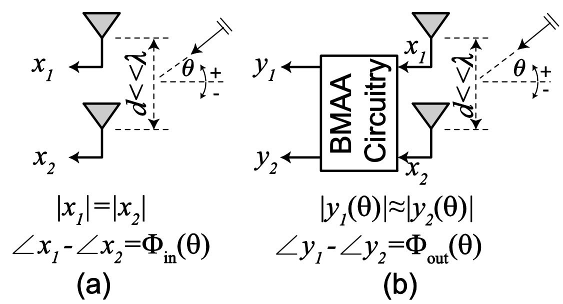
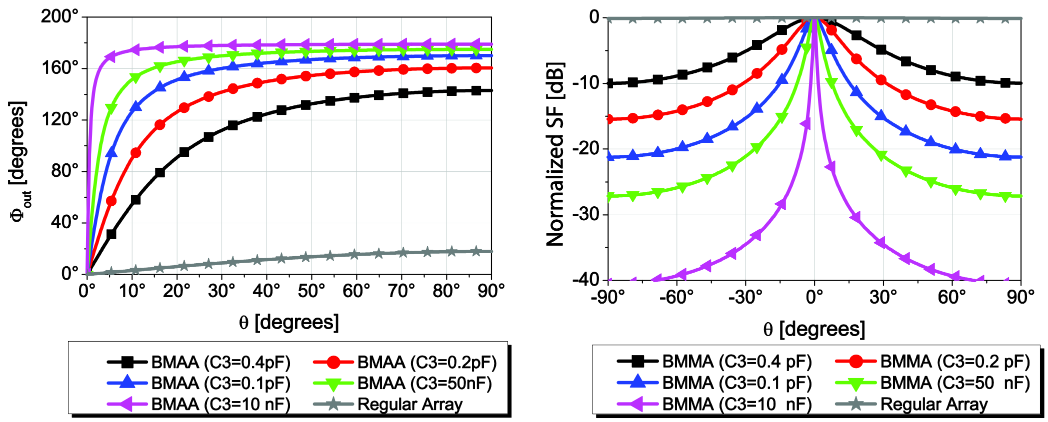


Fig. 5. (a) A two-element regular antenna array (RA) illuminated with an incident plane EM wave. (b) A two-element biomimetic antenna array (BMAA) based on the hearing mechanism of *O. Orchacrea* illuminated with a plane EM wave.

To demonstrate this, a BMAA composed of two isotropic receiving elements spaced $0.05\lambda_0$ apart and a regular two-element array with the same element type and spacing are analyzed. This BMAA is utilizing an equivalent circuit model similar to the one shown in Fig. 4(a). The values of the BMAA equivalent circuit model are R_1=R_2=1.1 Ω, C_1=C_2=1.75 pF, L_1-L_2=82 nH, and R_3=0 Ω. The values of the coupling capacitor C_3 are varied to study the effect of this parameter on the output phase difference between the two ports of the antenna. Fig. 6(a) shows the calculated $\Phi_{\text{out}}(\theta)$ as a function of θ for the regular array and the BMAA with various values of C_3. In this case, the BMAA circuitry is designed to ensure that $A(\theta) = B(\theta)$ (see (2)). For a small value of $d = 0.05\lambda_0$, the phase difference between the two outputs of the regular array remains very small as θ changes. However, the biomimetic array can provide a significantly larger output phase difference; Using (1) and (2), the corresponding sensitivity patterns of the two arrays are also calculated and shown in Fig. 6(b). Because the spacing between the two elements is extremely small, the regular array behaves almost similar to an isotropic receiver as seen from Fig. 6(b). On the other hand, the phase difference between the two outputs of the



(a) (b)

Fig. 6. (a) Variations of $\Phi_{\mathrm{out}}(\theta)$ vs. incidence angle, θ, for the regular array and BMAA shown in Fig. 5. The two outputs of the biomimetic array have a significantly larger phase difference compared to the regular array. (b) Normalized sensitivity factors of the regular array and the BMAAs with various phase responses shown in part (a). The capacitance values in the legend refer to the value of C3 in Fig. 4.

biomimetic array is significantly larger than that of the input phase difference. More importantly, the phase difference varies as a function θ and rapidly saturates to a level close to 180° as θ increases. This results in the sensitivity pattern of the biomimetic array to become significantly more directional than that of the regular array. Also, as observed from Fig. 6 and expected from (2), sharper variations of $\Phi_{\mathrm{out}}(\theta)$ vs. θ result in sharper sensitivity patterns. Achieving the same 3 dB sensitivity beam widths from regular arrays is only possible if a densely populated array with a significantly larger aperture size is used. For example, the sensitivity pattern achieved from a BMAA with C3=10 nF can be achieved from a regular antenna array with 100 elements and $\lambda/2$ spacing between the elements.

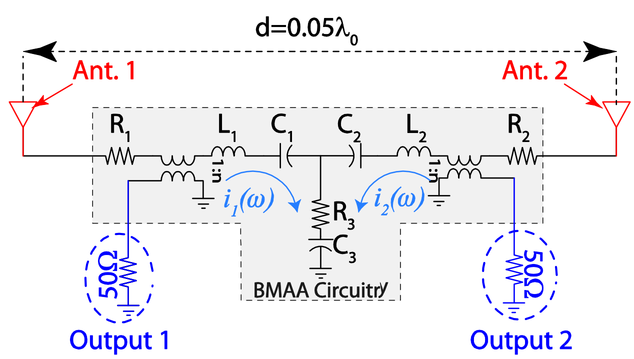


Fig. 7. Schematic of a two-element, electrically small biomimetic antenna array designed to mimic the performance of *Ormia Ochracea's* hearing mechanism. The antennas are omni-directional electrically small monopoles. The shaded region in the circuit is the BMAA circuitry depicted as a black box in Fig. 3. R_1 and R_2 model the radiation resistance of the two monopole antennas and R_3=0 Ω.

4. EXPERIMENTAL VALIDATION

To experimentally verify the theoretical results discussed in Section 3, a prototype of the two-element BMAA is designed, fabricated, and tested at 300 MHz. Figure 7 shows the topology of this antenna array. The structure is composed of two electrically small monopole antennas separated by a distance

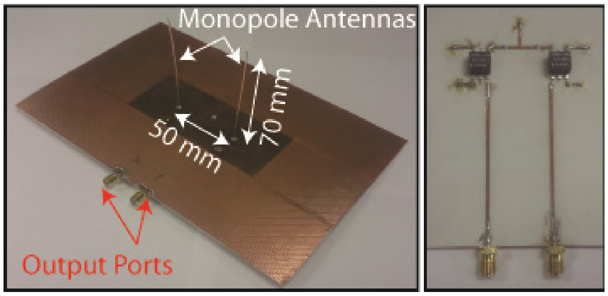


Fig. 8. Photograph of the fabricated prototype. Top view (left) shows the two electrically short monopole antennas constituting the BMAA and bottom view (right) shows the circuit elements.

of $0.05\lambda_0$ (5 cm at 300 MHz) and a coupled resonator circuit similar to the one shown in Fig. 4(a). The series resistors, R_1 and R_2, represent the radiation resistances of the two monopoles and C_1 and C_2 model the reactive part of their input impedances. In a plane normal to their axes, the monopoles are omni-directional antennas. To simplify the measurement process, the output loop currents are sampled with two series transformers and converted to output voltages measured at two 50Ω output ports. A photograph of the fabricated prototype is shown in Fig. 8. Two short wire sections are used to implement monopoles. The antennas are located on top of a ground plane with finite dimensions. A thin dielectric substrate with dielectric constant of 3.4 and thickness of 500 μm covers the bottom side of the ground plane. On the bottom side of this dielectric substrate, the BMAA circuit elements are located and connected to each other and to the monopole antennas using simple 50 Ω microstrip transmission lines. The connection between the monopole antennas and the transmission lines is achieved using simple through hole vias. The outputs of the two transformers are connected to the output ports of the antenna using two identical 50 Ω lines. In this BMAA, the values of the resistors, R_1 and R_2, and capacitors, C_1 and C_2, are determined from the input impedance of the two electrically small monopoles. Therefore, the only external circuit elements utilized are two inductors, L_1 and L_2, one capacitor, C_3, and two transformers that are used to convert the output loop currents into output port voltages that could be

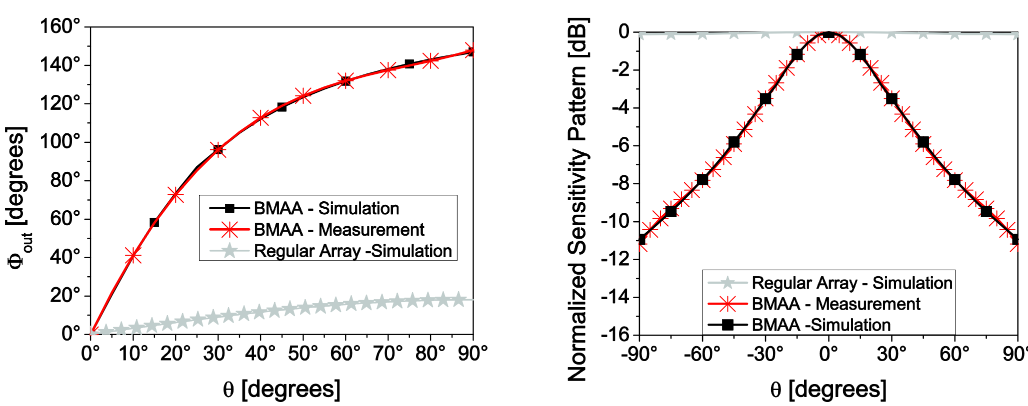


Fig. 9. (a) Measured and simulated phase responses of the biomimetic array shown in Fig. 7 and those of a regular array with identical elements and spacing (but without the BMAA circuitry). (b) Measured and simulated sensitivity patterns of the two arrays.

easily measured using a vector network analyzer (VNA).

The fabricated prototype is characterized by illuminating the BMAA with a plane wave from various incidence angles and measuring the two output signals. Figure 9(a) shows the phase difference between the two outputs of the biomimetic array and those of the regular array. The measured results agree very well with the theoretically predicted ones and confirm that the output phase difference of the BMAA is indeed enhanced compared to that of the regular array. Additionally, the measured sensitivity pattern of the BMAA is shown in Fig. 9(b) and compared to that of the regular array. As expected from (1)-(2), despite its extremely small aperture dimensions, the BMAA's sensitivity pattern is more directional compared to that of the regular array.

5. DISCUSSION AND POTENTIAL APPLICATIONS

In the most general case, one can envision three different outputs for the BMAA shown in Fig. 7. These include the loop currents i_1 and i_2 and the branch current flowing in the parallel branch $i_1 + i_2$. Denoting these three outputs as y_1, y_2, and y_3 respectively, we can obtain the following expression for $y_3 = i_3$ assuming the simplified equivalent circuit model shown in Fig. 4(a) and that $R_1=R_2$, $C_1=C_2$, and $L_1=L_2$:

$$y_3(\omega, \theta) = \frac{v_1(\omega, \theta) + v_2(\omega, \theta)}{Z_s + 2Z_p} \tag{4}$$

where $Z_s = R_1 + j\omega L_1 + (j\omega C_1)^{-1}$ and $Z_p = R_3 + (j\omega C_3)^{-1}$. For an electrically small receiving antenna with $d \ll \lambda$, $v_2(\omega, \theta) = v_1(\omega, \theta)e^{-jkd\sin\theta}$. Therefore, the angular dependency of y_3 vs. θ is in the form of:

$$y_3(\omega, \theta) \propto 1 + e^{-jkd\sin\theta} \tag{5}$$

which is the conventional definition of array factor and the same as the sensitivity pattern of the regular array. Therefore, in such a two-element BMAA, the angular variation of the signal $y_1 + y_2$ follows the angular variation of the regular array. Such a two-element BMAA with three different outputs and an electrically small aperture dimension acts as an omni-directional receiving antenna with the capability of resolving the direction of arrival of an incoming wave. This can be done using either a coherent system or an incoherent system. In a coherent measurement system, by measuring the phase difference between the two signals y_1 and y_2, the phase profiles shown in Fig. 6(a) can be derived. This output phase difference can be related to the input phase difference and the direction of arrival of the incoming EM wave. In this case, the BMAA enhances the output phase difference over the input phase difference. This makes detection of small phase differences easier and enhances the angular resolution of such a direction finding system.

Such a BMAA can also be used in conjunction with more advanced direction finding algorithms as well.

By examining (2) and considering that in this two-element BMAA, $|y_1(\theta)| \approx |y_2(\theta)|$, we can easily see that the maximum value of the sensitivity function is known a priori. Furthermore, the absolute value of this sensitivity pattern is only a function of direction of incidence of an EM wave and not of its power density. This concept can be used to design direction finding systems without the need for using coherent measurements. The sensitivity pattern of the BMAA can also be measured using simple power measurement as indicated in (3). Since the maximum value of the sensitivity factor is known a priori, measuring the sensitivity factor of the BMAA and comparing the value with the a priori known maximum value of the function can be used as a means of determining whether the signal is arriving from the direction of maximum sensitivity or not. Therefore, a system composed of a BMAA with electronically tunable sensitivity patterns and simple power detectors and comparators can be used as a basic direction finding system with electrically small dimensions.

The above discussions illustrate the possibility of using a BMAA composed of two closely spaced isotropic radiators ($d \ll \lambda_0$) to precisely resolve the direction of arrival of an incoming EM wave with an angular resolution that is only available from significantly larger antenna arrays. While this two-element BMAA has a significantly higher resolving capability compared to a regular array, this pattern does not translate to a higher directivity or gain for the BMAA. In other words, the maximum power that this array can collect is still limited by the physical size of its aperture. This is caused by the fact that the amplitudes of the two outputs of the BMAA, y_1 and y_2 in Fig. 5 vary as a function of θ. As described before, for a BMAA designed to have $|y_1(\theta)| \approx |y_2(\theta)|$, this amplitude variation is such that when $y_1(\theta)$ and $y_2(\theta)$ are coherently added together, i.e. $y_3(\theta) = y_1(\theta) + y_2(\theta)$ (the conventional array factor), the variations of y_3 vs. θ can be expressed using (1). Therefore, the conventional array factor and the directivity of this two-element BMAA are the same as those of a regular two-element array. Consequently, the highly directional sensitivity patterns of the array do not translate to higher received power or directivity compared to the regular array. *This also makes sense biologically, since insects can hear sounds arriving from almost any direction (low directivity) but can precisely resolve their directions of arrival to within 1°-2° angular resolution (highly directional sensitivity patterns).* Therefore, the term "directional hearing" which is commonly used to refer to the ability of a biological hearing mechanism in resolving the direction of arrival of a sound wave should not be mistaken with the concept of directionality in antenna theory which does indicate more received power.

The maximum gain of the BMAA prototype discussed in the previous section was also measured and found to be approximately 2 dB lower than the measured maximum gain of the regular array composed of the same receiving antennas but without the BMAA circuitry. This is attributed to the losses of the transformers, inductors, and capacitor used in the BMAA circuitry, which are not present in the regular array. In this prototype the value of R_3 is chosen to be 0 Ω and no external resistors is used. Our measurement results suggest that the reactive elements used in this BMAA circuitry do not noticeably increase the noise temperature of the antenna. Thus, it is expected that the output signal to noise ratio (SNR) of this BMAA is mainly determined by the available power at the antenna outputs. While such BMAAs do not offer higher directivity compared to their regular array counterparts, their directional sensitivity patterns could prove to be extremely useful in certain applications. Examples of these applications include small aperture radar systems, imaging systems, and RF sensors and will be discussed in the symposium.

6. CONCLUSIONS

A new concept for designing electrically small antenna arrays is proposed in this paper. This concept could lead to advancements in designing electrically small antenna arrays with capabilities that are not achievable from conventional antenna arrays with similar aperture dimensions. A biomimetic, electrically small antenna array modeled based on the hearing mechanism of a parasitoid fly was also demonstrated both theoretically and experimentally. It was shown that such antenna arrays demonstrate the resolving capabilities that are commonly seen in larger arrays. This concept could be beneficial in a wide range of application areas including miniature direction finding systems, high-resolution small aperture radar, miniaturized radio-frequency sensors, and high-resolution microwave imaging systems with small apertures.

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