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RESEARCH PAPER

A novel and simple expression to accurately calculate the resonant frequency of annular-ring microstrip antennas

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This paper proposes a novel and simple expression for effective radius of annular-ring microstrip antennas (ARMAs) obtained using a recently emerged optimization algorithm of artificial bee colony (ABC) in calculating the resonant frequency at dominant mode (TM_{11}). A total of 80 ARMAs having different parameters related to antenna dimensions and dielectric constants was simulated in terms of the resonant frequency with the help of an electromagnetic simulation software called IE3D™ based on method of moment. The effective radius expression was constructed and the unknown coefficients belonging to the expression were then optimally determined with the use of ABC algorithm. The proposed expression was verified through comparisons with the methods of resonant frequency calculation reported elsewhere. Also, it was further validated on an ARMA fabricated in this study. The superiority of the presented approach over the other methods proposed in the literature is that it does not need any sophisticated computations while achieving the most accurate results in the resonant frequency calculation of ARMAs.

Keywords: Antenna design, Modeling and measurements, Modeling, Simulation and characterizations of devices and circuits, Annular-ring microstrip antenna, Resonant frequency, Artificial bee colony algorithm

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I. INTRODUCTION

Annular-ring microstrip antenna (ARMA), formed by loading a circular slot in the center of the circular patch is one of the most studied microstrip antenna because of its several useful features [1–3]. The size of the resonant ring of the ARMA is substantially smaller than that of the corresponding circular patch. It therefore meets the requirements of miniaturized mobile applications. In ARMA, by a proper choice of the outer and inner radius of the ring, a significantly broader bandwidth than that of a circular disk microstrip antenna can be obtained [4]. The separation of resonant modes can also be controlled by the ratio of outer to inner radius [5]. Moreover, due to their gain-bandwidth characteristics and reduced size when they are excited in the dominant mode (TM_{11}), they have found applications in the medical field and in the satellite-based mobile communications [6].

From the open literature, most of the studies on the analyses and design of the ARMAs include high assumptions and rigorous calculations of Hankel and Fourier transforms and Bessel functions. In [6–9], the ARMA was theoretically investigated as if it was a resonator and several analyses were carried out for computing the resonant frequency. A set of mathematical tools such as vector Hankel transform, Galerkin method, and Green functions were utilized in the analysis of the ARMAs [10–13]. Methods based on the cavity model and the transmission line model was applied to investigate some parameters such as the resonant frequency, input impedance, and bandwidth [14–17]. Various characteristics of the antenna were analyzed with the matched asymptotic expansions technique, the perturbation approach [4] and the planar wave guide model [18]. The experimental studies concerning the ARMA were also presented to confirm the theoretical calculations in [5, 6, 11, 12, 17, 19–22].

The methods aforementioned for the analysis and design of ARMA depend on successive mathematical derivation using complicated functions and transform techniques. Therefore, the determination of resonant frequency takes much time and also needs knowledge of mathematics. It can be clearly seen from the literature [6–18], there is no simple and accurate expression for calculating the resonant frequency of the

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ARMA. In order to cope with this problem, in this work, an expression based on effective radius achieving the accurate resonant frequency has been proposed. Artificial bee colony (ABC) [23, 24] which is a recently introduced population-based optimization algorithm inspired by the intelligent foraging behavior of the honeybee was employed to form the effective radius expression of ARMA for TM_{11} mode. For deriving the effective radius expression, ARMAs with different electrical and physical parameters were simulated by the electromagnetic packed software IE3D^{TM} [25], based on method of moment (MoM) [26]. After the simulation process, according to these results various models for the effective radius expression including antenna dimensions and dielectric constants along with unknown optimization coefficients to be optimized were formed. In order to fit the calculated resonant frequency of effective radius expression in with the simulated ones, these parameters and respective simulated resonant frequencies were given as the input of the ABC to find the optimized unknown coefficients of the constructed effective radius expression. The accuracy and validity of the proposed expression was verified by comparing the resonant frequency results with those of reported elsewhere [8, 9, 17, 18] over the measurement data [5, 6, 11, 12, 17, 19–22]. It was also confirmed on an ARMA fabricated in this work.

II. THE ABC ALGORITHM

The ABC [23, 24] is a recently emerged population-based optimization algorithm finding near optimal solutions for the difficult optimization problems by the motivation foraging behavior of the honeybee swarm. In the ABC algorithm, three kinds of bee colonies consisting of the employed, the onlooker, and the scout are considered. Bees fly around to search in a multidimensional space, in order to find an optimal solution. The employed bees are assigned to specific food sources depending on their experiences. The onlooker bees decide the food source location based on observation of the dance of employed bees within the hive and adjust their positions. The scout bees carry out a random search for determining new food sources. Initially, the half of the total colony is appointed as the employed bee and the other half as the onlooker bees. The number of food sources representing the possible solution points around the hive is assumed to be equal to that of the employed bee. Thereafter, the food sources are exploited by the employed bees and the onlooker bees. Then, the employed bee which exhausts the food sources becomes a scout bee to search further food sources once again.

The pseudocode of the ABC algorithm given below:

Initialization phase: Scouts are randomly sent to the initial food sources.

(1) Initialize the population of solutions x_{ij}

$$x_i^j = x_{min}^j + rand[0, 1](x_{max}^j - x_{min}^j), \quad (1)$$

here $i = 1, 2, \ldots, FS$; $j = 1, 2, \ldots, D$. Where FS and D denote the size of food source and number of optimization parameters, respectively.

(2) Evaluate the population.

(3) Cycle = 1.

Repeat

Employed bee phase: Employed bees are sent to the food sources and determine their amounts.

(4) Produce new solutions (food source positions) v_{ij} in the neighborhood of x_{ij} for the employed bees using the formula

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}), \quad (2)$$

where $k \in 1, 2, \ldots, FS$ and $j \in 1, 2, \ldots, D$ are randomly chosen indexes. Although k is determined randomly, it has to be different from j. ϕ_{ij} is a random number between $[-1,1]$.

(5) Apply the greedy selection process between x_{ij} and v_{ij}.

Onlooker bee phase: The probability value of the sources are calculated by the onlooker bees

(6) Calculate fitness values for minimization problems using the following equation:

$$fit_i(x_{ij}) = \begin{cases} \dfrac{1}{1 + f_i(x_{ij})} & \text{if } f_i(x_{ij}) \geq 0, \\ 1 + abs(f_i(x_{ij})) & \text{if } f_i(x_{ij}) < 0. \end{cases} \quad (3)$$

(7) The probability value p_i with which x_{ij} is chosen by an onlooker bee can be calculated using the expression given:

$$p_i = \frac{fit_i(x_{ij})}{\sum_{n=1}^{FS} fit_n(x_{ij})}. \quad (4)$$

Normalize p_i values into [0,1].

(8) Produce the new solutions (new positions) v_i for the onlookers from the solutions x_i, selected depending on p_i, and evaluate them.

(9) Apply the greedy selection process for the onlookers between x_i and v_i.

Scout bee phase: If a source is abandoned by an employed bee, the scout bee is randomly sent to search the area for discovering new food sources.

(10) Determine the abandoned solution (source), if it exists, and replace it with a new randomly produced solution x_i for the scout bee using the equation (1).

(11) Memorize the best food source position (solution) achieved so far.

(12) Cycle = Cycle + 1.

Finalization

(13) Until cycle = Maximum Cycle Number (MCN)

At the initial phase, random values between two specified constraint values are generated for possible solution points regarding the food source location. The quality (fitness) of the generated values related to the amounts of the food is calculated to evaluate the profitability in first phase. In the onlooker bee phase, probability of the possible solution values is computed and new possible solutions are searched in the vicinity of the values with high probability. If the determined possible solution point does not improve after a specified number of trial limits, in the scout bee phase, a new value is randomly determined similar to the initial phase. Finally, the best solution point obtained is memorized. These phases sequentially continue until defined MCN.

III. THE EFFECTIVE RADIUS OF ARMA

Figure 1 shows the whole geometry of an ARMA. As seen from Fig. 1(a), ARMA has an annular-ring patch with inner radius of a_i and outer radius of a_o. From side view of the ARMA given in Fig. 1(b), the ring patch lies on the substrate having relative dielectric constant ε_r and overall on the ground plane. The resonant frequency of a circular disk microstrip antenna for the TM_{nm} mode is given by Balanis [1]

$$f_{nm} = \frac{X_{nm}c}{2\pi a\sqrt{\varepsilon_r}}, \tag{5}$$

where TM_{nm} is the mth zero of the derivative of Bessel function of order n, c is the velocity of electromagnetic waves in free space, ε_r is the relative dielectric constant of the substrate, and a is the radius of circular patch. The dominant mode is TM_{nm} $(n = m = 1)$, for which $X_{11} = 1.8412$ [1].

Since the ARMA is derived from the circular patch by slot loading, the resonant frequency expression of a circular disk microstrip can be modified for calculating the resonant frequency of the ARMA. For taking into account the effects of slot loading and fringing at the edges, the actual radius of the circular patch a is replaced by a newly introduced effective radius a_{eA} of the ARMA. Therefore, the resonant frequency for the ARMA at TM_{11} mode can be written as

$$f_{11} = \frac{X_{11}c}{2\pi a_{eA}\sqrt{\varepsilon_r}}. \tag{6}$$

In order to construct the effective radius expression a_{eA}, simulations by IE3D^{TM} have been performed for 80 ARMAs, which operate over the frequency range 0.66–3.71 GHz, with different dimensions and substrate dielectric constant values tabulated in Table 1. In the simulations, the antennas were assumed to have a probe feed of 50 Ω. For the meshing process, the cell/wavelength ratio was assumed as 40 in limit of 4 GHz. The built-in optimization module of the IE3D^{TM} was utilized to determine the feed point which gives the best return loss value with the objective function $s_{11}(\text{dB}) < -10$ for the resonant frequencies at TM_{11} mode.

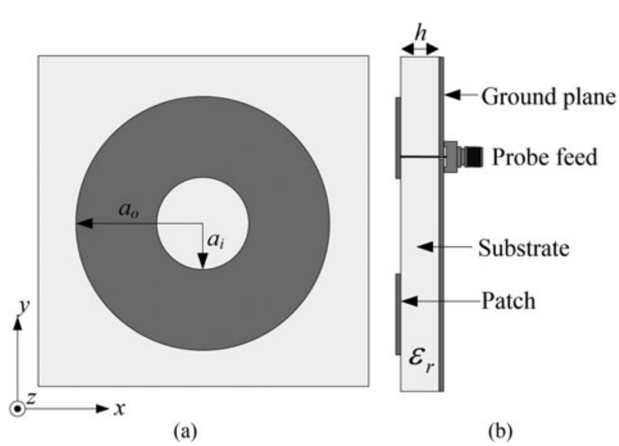

Fig. 1. The geometry of ARMA: (a) front view (b) side view.

Table 1. Physical and electrical parameters of simulated ARMAs.

Simulation number	Antenna dimensions (mm)			ε_r
	a_o	a_i	h	
4 × 20	15	2, 4, 6, 8, 10	0.64	4.5
	20	3, 6, 9, 12, 15		
	25	4, 8, 12, 16, 20		
	30	5, 10, 15, 20, 25		
	15	2, 4, 6, 8, 10	1.57	2.33
	20	3, 6, 9, 12, 15		
	25	4, 8, 12, 16, 20		
	30	5, 10, 15, 20, 25		
	15	2, 4, 6, 8, 10	2.5	9.8
	20	3, 6, 9, 12, 15		
	25	4, 8, 12, 16, 20		
	30	5, 10, 15, 20, 25		
	15	2, 4, 6, 8, 10	3.175	2.2
	20	3, 6, 9, 12, 15		
	25	4, 8, 12, 16, 20		
	30	5, 10, 15, 20, 25		

Various models of the effective radius expressions including the unknown coefficients (α_i) and the simulation parameters (a_o, a_i, h, and ε_r) were built to assign the best model which fits the simulation parameters in with the respective resonant frequencies. The unknown coefficients correspond to the optimization parameters (x_{ij}; $i = 1,2,\ldots,FS$; $j = 1,2,\ldots,D$) in the ABC algorithm. In our problem, FS and D denote the simulation number (SN) and the number of simulation parameters, respectively. The following fitness function was utilized in the ABC algorithm.

$$fit = \frac{1}{1 + TPE}, \tag{7}$$

where TPE is the total percentage error to be minimized and thus the fit approaches unity. TPE is defined as

$$TPE = \sum_{k=1}^{SN}\left[\left|\frac{f_{sim_k} - f_{cal_k}}{f_{sim_k}}\right| \times 100\right], \tag{8}$$

where f_{sim} and f_{cal} are the simulated and calculated resonant frequency values, respectively. In the optimization process with ABC, the colony size, MCN, limit values, initial minimum, and maximum values were chosen as 20, 1000, 20, −2, and 2, respectively. In order to assign proper effective radius expression, a series of experiments were carried out, and the expression a_{eA} which produces satisfactory results has been constructed as

$$a_{eA} = \frac{\alpha_1(a_o + a_i)}{\left(1 + \alpha_2\frac{a_o}{a_i} + \left(\frac{h}{(a_o + \alpha_3 a_i)\varepsilon_r}\right)\right)\left(\alpha_4\frac{a_o}{h} + \alpha_5\frac{a_o}{a_i} + \alpha_6\varepsilon_r\left(1 - \frac{h}{a_i}\right) + 1\right)}. \tag{9}$$

Note that the effective radius expression models which were simpler and more complicated than that given by equation (9) were also tried. It was seen that the results of simpler models were not in good agreement with the simulation

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Table 2. Coefficient values for effective radius expression of ARMA determined by the ABC algorithm.

Index (j)	1	2	3	4	5	6
α_j	0.85	−0.007	−1.1	−0.05	−0.13	0.18

results, on the other hand the more complicated forms provide little improvement in the *TPE* value. The unknown coefficients of the effective radius expression were then optimally determined and these coefficients are given in Table 2. By substituting the coefficient values given in Table 2 into equation (9), the effective radius is then obtained as follows:

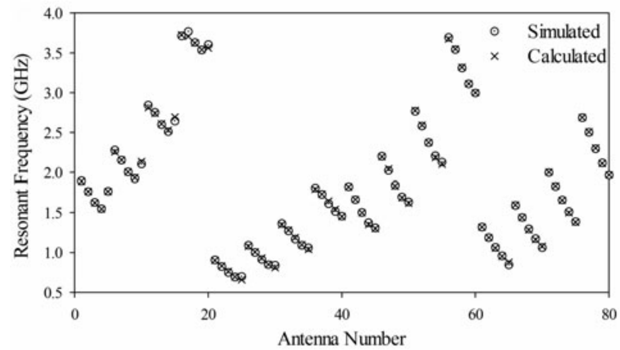

Fig. 2. The simulated and calculated resonant frequency.

$$a_{eA} = \frac{0.85(a_o + a_i)}{\left(1 - 0.007\frac{a_o}{a_i} + \left(\frac{h}{(a_o - 1.1a_i)\varepsilon_r}\right)\right)\left(-0.05\frac{a_o}{h} - 0.13\frac{a_o}{a_i} + 0.18\varepsilon_r\left(1 - \frac{h}{a_i}\right) + 1\right)}. \quad (10)$$

Eventually, the resonant frequency of an ARMA can be calculated by substituting the effective radius expression given in equation (10) into equation (6). It should be noted that dielectric constant ε_r is utilized in our resonant frequency expression rather than the effective dielectric constant ε_{eff} [1], for the sake of simplicity, since a_{eA} has already included the fringing effects. It should be also noted that the proposed effective annular radius expression has been formed by means of the simulated ARMAs with physical and electrical parameters given in Table 1.

IV. NUMERICAL RESULTS

The resonant frequency results of the proposed expression obtained by the ABC algorithm and those of the numerical simulations for 80 ARMAs are plotted in Fig. 2. Average percentage error (APE) has been obtained as 0.84% for the self-consistent test. This self-consistent agreement between the simulated and calculated results supports the accuracy of the new effective radius expression. Furthermore, in order to compare the ABC algorithm with another optimization algorithm such as genetic algorithm (GA) [27], the unknown coefficients of the proposed expression model in equation (9) were determined by standard GA. The APE for the expression optimized by GA has been obtained as 1.04%.

In order to verify the validity of the proposed expression, the resonant frequency results calculated in this study were also compared with those of several suggestions reported elsewhere [8, 9, 17, 18] over measurement results of ARMAs published earlier in the literature [5, 6, 11, 12, 17, 19–22]. These comparative results are given in Table 3 and the corresponding percentage errors are tabulated in Table 4. The resonant frequency results simulated using IE3D™ and HFSS™ are also given in Table 3 so as to confirm the simulations performed in this study. It is clearly seen that our simulated results agree well with measured ones. These results demonstrate that the simulation process for 80 ARMAs is very accurate, and thus the derived effective radius expression produces reliable results.

The suggestions for calculating the resonant frequency of the measured ARMAs previously published give comparable results; however, some calculations are in good agreement with measured data, and others are far off. The suggested

Table 3. Comparative results for resonant frequencies of ARMAs.

ARMA	Antenna parameters				Resonant frequencies (GHz)							
	Dimensions (mm)				Simulated			Calculated				
	a_o	a_i	h	ε_r	IE3D™	HFSS™	Measured	This study	[8]	[9]	[17]	[18]
[5]	50	25	1.59	2.32	0.88	0.88	0.878	0.881	0.848	0.886	0.877	0.854
[6]	20	10	3.18	2.32	2.50	2.41	2.450	2.477	2.171	2.337	2.297	2.149
[11]	50	25	1.59	2.32	0.88	0.88	0.891	0.881	0.848	0.886	0.877	0.854
[12]	14.2	7.1	0.355	2.65	2.88	2.89	2.880	2.891	2.786	2.907	2.882	2.811
[17]	17.2	8.6	1.6	4.2	2.03	1.98	1.989	2.007	1.847	2.035	1.997	1.855
[19]	70	35	1.59	2.32	0.62	0.62	0.625	0.623	0.604	0.627	0.622	0.609
[20]	70	35	1.59	2.3	0.63	0.62	0.626	0.625	0.606	0.629	0.625	0.612
[21]	30	10	0.8	4.4	1.21	1.20	1.243	1.201	1.146	1.213	1.590	1.171
[22]	35	17.5	1.53	4.3	0.95	0.94	0.940	0.943	0.889	0.954	0.941	0.897
[22]	17.5	8.75	1.53	4.3	1.97	1.91	1.960	1.943	1.792	1.972	1.936	1.801
This study	13	2.0	2.54	4.5	3.03	2.97	3.000	3.048	3.074	2.800	8.392	2.518

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Table 4. Percentage errors for resonant frequencies.

ARMA	Errors (%) This study	[8]	[9]	[17]	[18]
[5]	0.34	3.42	0.91	0.11	2.73
[6]	1.10	11.39	4.61	6.24	12.29
[11]	1.12	4.83	0.56	1.57	4.15
[12]	0.38	3.26	0.94	0.07	2.40
[17]	0.90	7.14	2.31	0.40	6.74
[19]	0.32	3.36	0.32	0.48	2.56
[20]	0.16	3.19	0.48	0.16	2.24
[21]	3.38	7.80	2.41	27.92	5.79
[22]	0.32	5.43	1.49	0.11	4.57
[22]	0.87	8.57	0.61	1.22	8.11
This study	1.60	2.47	6.67	179.73	16.07
APE (%)	0.95	5.53	1.94	19.82	6.15

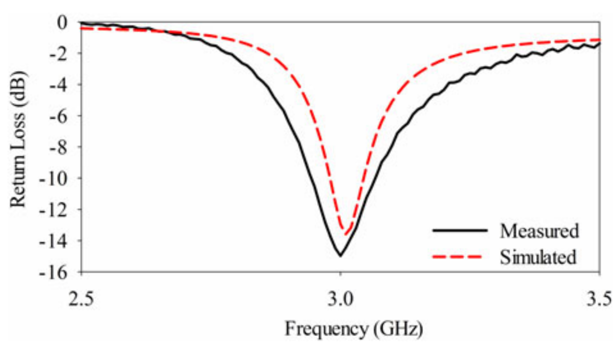

Fig. 3. The simulated and measured return loss plots.

methods produce more precise results for some particular antennas, e.g. the formulation method by Pintzos and Pregla [9] for the antenna [11], and the formulation method [17] for the antennas [5, 12, 17, 19, 20, 22]. However, the APE value of our proposed expression is 0.95, while it is 5.53, 1.94, 19.82, and 6.15 by suggested methods [8, 9, 17, 18], respectively. On the other hand, the APE value for our expression stays within 3.4, while it remains within 11.4, 6.7, 179.7, and 16.1 in [8, 9, 17, 18], respectively. Therefore, our resonant

Table 5. The valid range of antenna parameters for the proposed expression.

Parameter	Minimum	Maximum
h (mm)	0.64	3.175
h/λ_d	0.0039	0.059
f (GHz)	0.66	3.73
a_i/a_o	0.13	0.83

λ_d is the wavelength in the substrate.

frequency results are generally in good agreement as compared with those calculated by other suggestions [8, 9, 17, 18]. It means that the proposed expression is more stable and reliable than those suggested in the literature. Moreover, the expression proposed here not only provides the better agreement, but also allows us to calculate the resonant frequency of ARMA in a very simple manner without dealing with any sophisticated calculations including complicated functions and transforms.

The accuracy and validity of the proposed expression were also tested on the measurement data of ARMA, which were fabricated in this work using the material of Rogers^{TM} TMM4. The simulated and measured return loss plots obtained by using an AgilentE5071B ENA Series RF network analyzer are illustrated in Fig. 3. Note that the measurement results may include some tolerances because of material production, geometry etching, and feed connector misalignment in the fabrication process. The measured and calculated resonant frequency results of the fabricated antenna are also given in Table 3, and it can be seen that the proposed formula for resonant frequency of the ARMA provides the best fit for the measurement.

The effective radius expression proposed in this study was validated for the parameter ranges given in Table 5 and it allows us to compute the resonant frequency with high accuracy in a simple manner as compared with the methods for ARMAs presented in the literature.

Figure 4 shows the measured two-dimensional (2D) radiation patterns of E_ϕ and E_θ field for the fabricated ARMA at 3 GHz. It is seen that the radiation patterns have good performance and approaches omnidirectional radiation

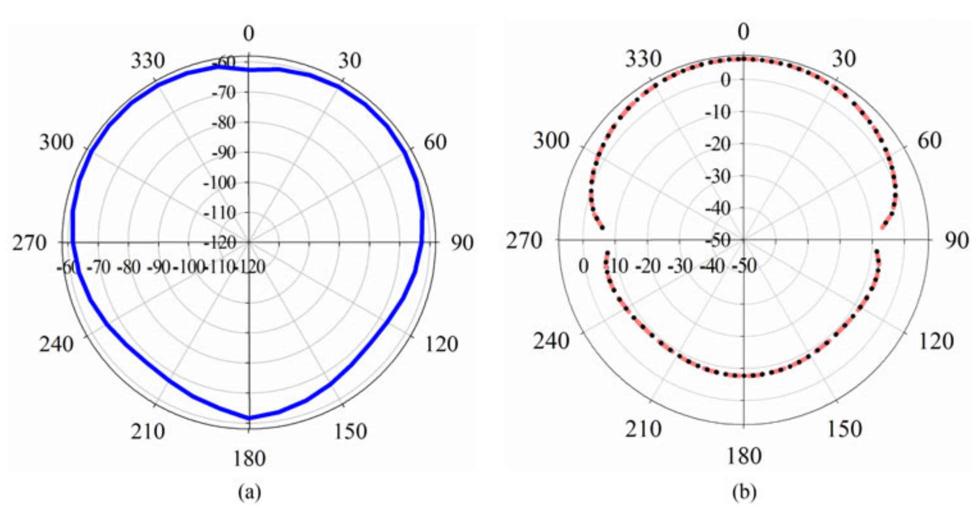

Fig. 4. The measured radiation patterns of fabricated ARMA at 3 GHz: (a) —— E_ϕ for $\theta = 90^\circ$ (b) - - - E_θ for $\phi = 0^\circ$ and •••• $\phi = 90^\circ$.o

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characteristics. The measured gain and half-power beam width (HPBW) achieved are 6.545 dBi and 110.5°, respectively.

It can be clearly seen from the results given above that our calculated results using the proposed expression are better than the determined ones by other suggestions [8, 9, 17, 18]. This good agreement between the measured and our calculated resonant frequency values supports the validity of the effective radius expression obtained using the ABC algorithm. Using the expression presented here, one can easily calculate the resonant frequency of the ARMAs using a scientific calculator since it does not require complicated mathematical transformations of sophisticated functions.

V. CONCLUSION

In this study, a novel and simple effective radius expression which results in accurately calculating the resonant frequency of the ARMAs has been presented. To manage this goal, an expression was derived by utilizing the simulation data of 80 ARMA having different patch dimensions and dielectric constant values, together with ABC algorithm which is one of the most recently introduced swarm-based optimization method. The resonant frequency results obtained in this study are comparable with those of the methods proposed in the literature and the various measurement antenna data reported elsewhere. It was demonstrated that the resonant frequency values obtained from the effective radius expression are in very good agreement with the measured results as compared with those calculated by the other methods earlier. It is concluded that the advantages of expression presented in this work are the simple and the accurate.

REFERENCES

[1] Balanis, C.A.: Antenna Theory: Analysis and Design, Wiley-Interscience, New Jersey, USA, 2005.

[2] Agrawal, A.; Singhal, P.K.; Jain, A.: Design and optimization of a microstrip patch antenna for increased bandwidth. Int. J. Microw. Wirel. Tech., **5** (2013), 529–535.

[3] Khare, A.; Nema, R.: Optimization of a broadband directional gain microstrip patch antenna for X Ku band application. Int. J. Microw. Wirel. Tech., **5** (2013), 77–84.

[4] Chew, W.: A broad-band annular-ring microstrip antenna. IEEE Trans. Antennas Propag., **30** (1982), 918–922.

[5] Dahele, J.S.; Lee, K.-F.; Wong, D.: Dual-frequency stacked annular-ring microstrip antenna. IEEE Trans. Antennas Propag., **31** (11) (1987), 1281–1285.

[6] Bahl, I.J.; Stuchly, S.S.; Stuchly, M.A.: A new microstrip radiator for medical applications. IEEE Trans. Microw. Theory Tech., **28** (12) (1980), 1464–1469.

[7] Wolff, I.; Knoppik, N.: A new microstrip radiator for medical applications. Electron. Lett., **7** (26) (1971), 779–781.

[8] Wu, Y.S.; Rosenbaum, F.J.: Mode chart for microstrip ring resonators. IEEE Trans. Microw. Theory Tech., **21** (7) (1973), 487–489.

[9] Pintzos, S.G.; Pregla, R.: A simple method for computing the resonant frequencies of microstrip ring resonators IEEE Trans. Microw. Theory Tech., **26** (10) (1978), 809–813.

[10] Ali, S.M.; Chew, W.; Kong, J.: Vector Hankel transform analysis of annular-ring microstrip antenna. IEEE Trans. Antennas Propag., **30** (4) (1982), 637–644.

[11] Fan, Z.; Lee, K.-F.: Hankel transform domain analysis of dual-frequency stacked circular-disk and annular-ring microstrip antennas. IEEE Trans. Antennas Propag., **39** (6) (1991), 867–870.

[12] Liu, H.; Hu, X.F.: An improved method to analyze the input impedance of microstrip annular-ring antennas. J. Electromagn. Wave, **10** (6) (1996), 827–833.

[13] Motevasselian, A.: Spectral domain analysis of resonant characteristics and radiation patterns of a circular disk and annular ring microstrip antenna on uniaxial substrate. Prog. Electromagn. Res., **21** (2011), 237–251.

[14] Richards, W.F.; Jai-Dong, O.; Long, S.: A theoretical and experimental investigation of annular, annular sector, and circular sector microstrip antennas. IEEE Trans. Antennas Propag., **32** (6) (1984), 864–867.

[15] Bhattacharyya, A.K.; Garg, R.: Input impedance of annular ring microstrip antenna using circuit theory approach. IEEE Trans. Antennas Propag., **33** (4) (1985), 369–374.

[16] Sathi, V.; Ghobadi, C.H.; Nourinia, J.: Optimization of circular ring microstrip antenna using genetic algorithm. Int. J. Infrared Millim. Waves, **29** (10) (1997), 897–905.

[17] Kumar, R.; Dhubkarya, D.C.: Design and analysis of circular ring microstrip antenna. Global J. Res. Eng., **11** (1) (2011), 1–5.

[18] Bahl, I.J.; Stuchly, S.S.: Closed-form expressions for computer-aided design of microstrip ring antennas. Int. J. Microw. Mill., **2** (3) (1992), 144–154.

[19] Dahele, J.S.; Lee, K.-F.: Characteristics of annular-ring microstrip antenna. Electron. Lett., **18** (24) (1982), 1051–1052.

[20] Lee, K.-F.; Dahele, J.S.; Ho, K.Y.: Annular-ring and circular-disc microstrip antennas with without air gaps, in 13th European Microwave Conf., Nurnberg, Germany, 1983.

[21] Row, J.-S.: Dual-frequency circularly polarised annular-ring microstrip antenna. Electron. Lett., **40** (3) (2004), 153–154.

[22] Shinde, J.; Shinde, P.; Kumar, R.; Uplane, M.D.; Mishra, B.K.: Resonant frequencies of a circularly polarized nearly circular annular ring microstrip antenna with superstrate loading and airgaps, in Kaleidoscope: Beyond the Internet – Innovations for Future Networks and Services, ITU-T, 2010.

[23] Karaboga, D.; Basturk, B.: A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. J. Global Optim., **39** (3) (2007), 459–471.

[24] Akdagli, A.; Toktas, A.: A novel expression in calculating resonant frequency of H-shaped compact microstrip antennas obtained by using artificial bee colony algorithm. J. Electromagn. Wave, **24** (14) (2010), 2049–2061.

[25] IE3D™, version 14, Menthor graphics corporation, Boeckman Road Wilsonville, OR 9707.

[26] Harrington, R.F.: Field Computation by Moment Methods, IEEE Press, Piscataway, NJ, 1993.

[27] Davis, L.D.: Handbook of Genetic Algorithms, Van Nostrand Reinhold, New York, 1991.

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