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Compact and Low-profile Frequency Agile Loop Antenna Integrated with Inductors

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Abstract— We present a frequency agile loop antenna which consists of a suspended transmission line and two inductors. Using appropriate inductors, the operating frequency of the antenna can be controlled without seriously sacrificing its performance. We derived an equivalent circuit of this proposed compact and low-profile antenna. Results from some prototypes showed that a frequency tuning range as high as 870 MHz can be achieved using off-the shelf inductors. In the case of integrating two inductors of 33 nH, an electrical size of the antenna as small as $0.118 \lambda \times 0.013 \lambda \times 0.047 \lambda$ is achieved.

I. INTRODUCTION

As the modern wireless communication devices become compact and with the significant increasing demand of low frequency applications, the development of simple small antenna structures with low profile, and light weight have been one of the most challenging research area among antenna designers. Traditional techniques for miniaturizing antenna include creating the current path long using shorting pins [1], slots [2], and meander lines [3], or making electrical dimension long by employing a high dielectric material [4]. The main disadvantages of these techniques cause inescapable problems such as narrowing bandwidth, increasing cross polarization level and decreasing radiation efficiency. A circular disk loaded monopole antenna [5] which uses an electromagnetic coupling and a folded conical helical antenna [6] have been reported to increase the bandwidth with a compact size. However these structures are complicated to fabricate.

In this paper, a simple compact frequency tunable loop antenna and light weight is proposed. This antenna structure consists of two rectangular substrates, two posts and two inductors. Altering the inductor values, the operating frequency can not only be shifted but also the input impedance can be easily matched without degrading the fractional input impedance bandwidth. This paper is made up of five main sections including the introduction, and in section 2, we discuss the concept of miniaturizing a loop antenna by integrating inductors and introduce the configuration of the proposed antenna. The equivalent circuit model of the proposed antenna structure is presented in section 3, and we also present some results from both full wave and circuit model analysis with varying inductor pairs. In section 4, we

present the measured results to validate the simulated results, and finally, we conclude this paper in section 5.

II. CONFIGURATION OF PROPOSED ANTENNA

Figure 1 (a) shows a loop antenna mounted on a ground plane. The directions of current distributions on two vertical wires are the same, and its fitting that these currents can contribute to the radiation energy. The current along the horizontal wire has a different role, and these currents play a role of keeping resonance condition and do not contribute to the radiation energy. Therefore, one can incorporating a pair of inductors on the horizontal wire in order to give a phase delay with a small wire length, and reduce the horizontal wire length. The induced phase delay from the integrated inductors maintains the resonance condition, so that same current distribution with the conventional loop antenna is expected. We present this concept of miniaturized antenna in Figure 1 (b) with current distribution. Note that the inductors are located at edges of the horizontal wire to contribute a large phase delay in given inductance of the inductors, because of the high current concentration at the edges.

Fig. 1 Configuration of a loop antenna mounted on a ground plane and its current distribution. (a) without inductor. (b) with inductors.

In order to implement this miniaturization idea, we have designed a 3-dimensional loop antenna with two inductors as shown in Figure 2. The proposed antenna consists of two layers, an upper layer and a bottom layer, which are a rectangular substrate of permittivity ϵ_r . The distance between two layers is h . The bottom layer acts as a ground plane having a length of gl ($= line_l + 10$ mm) and a width of gw ($= line_w + 15$ mm). A transmission line having a length of $line_l$ and a width of $line_w$ is placed on the upper layer. At the end of the transmission line, two posts connect the transmission line through the ground plane. The diameters of the posts are p_1 and p_2 . Two inductors (L_1, L_2) are integrated between the posts and the transmission line.

Fig. 2 Configuration of the proposed antenna.

III. EQUIVALENT CIRCUIT MODEL

Figure 3 is the derived equivalent circuit of the proposed antenna, that can be regarded as a good tool in understanding the operating mechanism of the antenna. The straight transmission line, length of $line_l$ and width of $line_w$, is simply modeled as a transmission line, length of $line_l$ and width of $line_w$, of which characteristic impedance is Z_0 and propagation constant is β . Since the two posts act as the main radiation elements, the posts are modeled as a radiation resistance, R_r . This radiation resistance, R_r , makes the response of the circuit more broadband. Although several mutual inductive couplings between inductors exist on the equivalent circuit, only one mutual inductive coupling (M) between L_1 and L_2 , is considered for simplification. In order to verify the equivalent circuit of the antenna, the results from a

Fig. 3 Equivalent circuit model of the proposed antenna.

full-wave simulation and those from a circuit simulation are compared in Table 1. CST's MWS full-wave simulator is used for full-wave analysis, and Agilent's ADS is used for circuit analysis. The parameters are set as $h = 3$ mm, $line_l = 20$ mm, $line_w = 1$ mm, $p_1 = 0.3$ mm, $p_2 = 0.5$ mm and $\epsilon_r = 1$. Resonant frequency (f_0), input impedance at resonant frequency (Z_r), and input impedance bandwidth (BW) are summarized in Table 1 for several different values of L_1 and L_2 . This Table shows a comparison between full-wave and equivalent circuit model results. (L_1, L_2 : inductance of integrated inductor (nH), M : mutual coupling (nH), f_0 : resonance frequency (GHz), Z_r : input impedance at resonance frequency (Ω), BW: input impedance bandwidth (MHz)).

In Table 2 summarizes the results from full-wave analysis with different pairs of L_1 and L_2 with the following antenna dimensions: $h = 10$ mm, $line_l = 20$ mm, $line_w = 1$ mm, $p_1 = 0.3$ mm, $p_2 = 0.5$ mm and $\epsilon_r = 1$.

TABLE I
FULL-WAVE AND CIRCUIT ANALYSIS

Inductance			Full-wave analysis			Circuit model analysis		
L1	L2	f0	Z	BW	M	f0	Z	BW
0	0	6.13	6	n/a	0	7.5	6	n/a
1	1	5.36	5.8	n/a	1	5.72	6	n/a
10	1	4.07	17	n/a	2	4	20	n/a
20	1	3.62	5.26	52.6	3	3.78	56.8	38
1	10	3.95	3.9	n/a	2	4.20	3.62	n/a
1	20	3.52	3.45	n/a	3	3.79	3.17	n/a

TABLE II
FULL-WAVE ANALYSIS

Inductance		Full-wave analysis			Antenna Size
L1	L2	f0	Z	BW	$line_l \times line_w \times h$
0	0	4.36	42.66	8.2	$0.291 \lambda \times 0.014 \lambda \times 0.145 \lambda$
14	10	2.77	54.57	3.33	$0.185 \lambda \times 0.009 \lambda \times 0.092 \lambda$
30	30	1.93	51.14	2.42	$0.129 \lambda \times 0.006 \lambda \times 0.064 \lambda$
65	100	1.23	48.35	2.09	$0.082 \lambda \times 0.004 \lambda \times 0.041 \lambda$
110	220	0.91	54.30	2.13	$0.061 \lambda \times 0.003 \lambda \times 0.030 \lambda$
190	400	0.74	54.60	2.20	$0.049 \lambda \times 0.002 \lambda \times 0.025 \lambda$

IV. PROTOTYPE RESULTS

In order to validate the simulation results, several proposed antennas have been fabricated with different combinations of L_1 and L_2 . Figure 4 shows the fabricated antennas with and without inductors. The design parameters are $line_l = 28$ mm, $line_w = 3$ mm, $h = 11.2$ mm and $p_1 = p_2 = 0.9$ mm. The substrate is FR4 of 0.8 mm thickness, and the inductors of LQW18A series of Murata are used.

Fig. 4 Fabricated proposed antennas. (a) without inductor. (b) with inductor.

Fig. 5 Measured return loss with different inductor pairs.

Figure 5 shows the measured and simulated return losses of the proposed antennas with 3 different inductor pairs, ($L_1 = 0$ nH, $L_2 = 0$ nH), ($L_1 = 10$ nH, $L_2 = 0$ nH), ($L_1 = 33$ nH, $L_2 = 33$ nH). From this figure, it can be noted that the proposed antenna's operating frequency can be controlled using simple passive devices. As the inductor pairs increase from (10 nH, 5.6 nH) to (33 nH, 33 nH), the measured center operating

frequencies decrease from 2.19 GHz to 1.26 GHz, and those of the simulated ones are 2.07 GHz and 1.2 GHz. The measured input impedance bandwidths of the two cases are 102 MHz (4.7%) and 28 MHz (2.2%), and those of the simulated ones are 101 MHz (4.9%) and 33 MHz (2.8%). The minor differences between the measured and simulated results might be due to fabrication error since the fabrications are not optimized. Note that the electrical dimension, $line_l \times line_w \times h$, of the fabricated one with the inductor pairs, $L_1 = 33$ nH and $L_2 = 33$ nH, is only $0.118 \lambda \times 0.013 \lambda \times 0.047 \lambda$. If a higher value of inductance combination is used, the size can be further decreased without degrading the fractional bandwidth.

Fig. 6 Measured radiation patterns of the antenna at 2.22 MHz ($L_1 = 10$ nH, $L_2 = 5.6$ nH). (a) x - y plane. (b) y - z plane.

The radiation patterns of the fabricated antenna with $L_1 = 10$ nH, $L_2 = 5.6$ nH at 2.22 GHz are measured using a 5° resolution in the anechoic chamber, and the results at the main two cuts, x - y plane and y - z plane, are presented in Figure 6. An omnidirectional and a symmetric radiation patterns are observed at x - y plane and y - z plane, respectively. These radiation patterns are similar to those of a monopole antenna. These radiation characteristics are due to the fact that dominant radiation elements are the two posts. The measured radiation efficiency is 32.2 %.

V. CONCLUSION

In this paper, we have demonstrated a miniaturization technique that can be applied to a wide range of microwaves systems. We have successfully demonstrated the feasibility of this technique using a suspended loop antenna and integrating a pair two inductors (L_1 and L_2) within high currents density regions. The results show that the resonant frequency becomes lower and the input resistance becomes higher as L_1 is increased, but on the other hand both resonant frequency and input resistance become lower as L_2 is increased. These characteristics allow not only the antenna to have the attractive feature of tunable operating frequency mechanism but also make the antenna electromagnetically small. One of the fabricated antennas has only $0.118 \lambda \times 0.013 \lambda \times 0.047 \lambda$ electrical size at 1.2 GHz. Another key advantage of this proposed antenna is its constant fraction input impedance bandwidth across its entire tunable frequency range. The measured results are compared to the predicted results, and the agreement is good.

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