Design of electrically small planar antennas using inductively coupled feed

H. Choo and H. Ling

A class of electrically small planar antennas with an inductively coupled feed structure is proposed. The antennas are optimised using the Pareto genetic algorithm. These antennas are self-resonant and capable of good efficiency and bandwidth performance without any additional matching networks. Several prototypes are fabricated and measured and the results agree well with simulation. A lumped element circuit model is presented to explain the operating principle of these antennas.

Introduction: Electrically small antennas are currently in demand in many wireless communication applications. However, as the size of an antenna is reduced, both its efficiency and bandwidth decrease. Furthermore, the input resistance of an antenna drops rapidly as its size is reduced, making it difficult to impedance match the antenna to the rest of the RF system. Recently, genetic algorithms (GA) have been reported for the design of electrically small wire antennas [1, 2]. In [2], we found that for very small monopole antennas ($k_r < 0.5$), the GA-optimised wire shapes take on a unique feature, namely, a point along the wire is shorted to the ground plane. A natural interpretation of this structure is that the first portion of the wire structure acts as an inductively coupled feed, while the remaining portion acts as the radiating part of the antenna. This inductive coupling mechanism is favoured by the GA to boost up the input resistance for electrically small antennas.

In this Letter, we exploit this design concept and propose an electrically small, planar antenna with an inductively coupled feed. The antenna body consists of a spiral structure, with a rectangular loop underneath the antenna body. The Numerical Electromagnetics Code (NEC) [3] in conjunction with the Pareto GA [4] is used to optimise the wire windings and feed dimensions based on bandwidth, efficiency and size considerations. Optimal designs are generated and shown to be electrically small, self-resonating and capable of good efficiency and bandwidth characteristics without the need for any additional matching networks. Several prototypes are fabricated and measured in the laboratory. A simple lumped-element circuit model is proposed to explain the operating principles of the antenna.

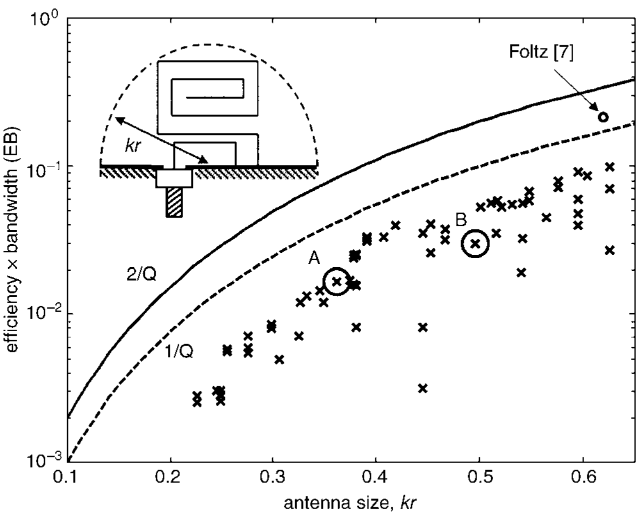

Fig. 1 *Efficiency-bandwidth product (EB) of inductively coupled design against antenna size*

× optimised GA designs
— 1/Q limit - - - 2/Q limit

Design methodology and results: The proposed antenna structure is shown in the inset in Fig. 1. The inductively coupled feed configuration entails a small rectangular loop underneath the antenna body. One end of the loop is connected to the coaxial input, and the other end is shortened to the ground plane. A spiral winding is used for the antenna body to achieve small size (meander winding was also tried, with inferior results [5]). The strength of the inductive coupling is controlled by the distance between the feed and the antenna body, as well as by the area of the loop. The resonant frequency and the Q of the antenna are largely controlled by the width, height and number of wire turns of the antenna body. The target design frequency is chosen at 400 MHz and an infinite ground plane is assumed in the design. Copper wire of radius 0.5 mm is used for both the antenna body and the feed. The antenna is designed to match to a 50 Ω characteristic impedance.

We employ the Pareto GA to carry out a multi-objective optimisation in terms of the best bandwidth, highest efficiency and smallest antenna size. In the Pareto GA, the design parameters are encoded into a binary chromosome. After evaluating the three objectives for each sample structure using NEC, all the samples of the population are ranked using the non-dominated sorting method. Based on the rank, a reproduction process is performed to refine the population into the next generation. The final converged 'Pareto front' contains optimised antenna designs that are optimal in at least one out of the three objectives. Fig. 1 shows the resulting efficiency-bandwidth product (EB) of the optimised GA designs against antenna size. The size of the antenna is defined by k_r, where k is the wave number and r is the radius of the smallest semi-circle enclosing the whole antenna structure. For comparison, we plot the $1/Q$ and $2/Q$ limits for small antennas [6], as well as the EB of the disk-loaded monopole from [7] in the same Figure. We observe that the EB of our proposed antennas are below that of the disk-loaded monopole. However, our designs use only planar wires without any material loading. Further, the same design methodology can easily cover a wide range of sizes from $0.2 < k_r < 0.6$. The EB performance of our designs approximately track the $1/Q$ limit for $k_r > 0.4$. For smaller sizes, the designs deviate more from the limit, indicating that it is more challenging to design very small antennas.

To verify our GA results, the designs at sample points A and B in Fig. 1 were built and measured. The k_r of antennas A and B are, respectively, 0.36 and 0.49. The inset of Fig. 2 shows the detailed dimensions of antenna A. A 1.2 m × 1.2 m conducting plate was used as the ground plane in the measurement. Fig. 2 shows the VSWR and the efficiency of antenna A against frequency from simulation and measurement. The measured resonant frequency of the prototype (395 MHz) is about 2.0% lower than the design (403 MHz), and the measurement data are shifted up in the plot by that amount for easier comparison. The resulting bandwidth from measurement is about 1.95%, which is similar to the value of 1.77% from simulation (based on VSWR < 5.85 or $|S_{11}| \leq -3$ dB). In the same Figure, we also plot the efficiency measurement of the antenna using the Wheeler cap method [8]. The measured efficiency of 84% matches the simulated efficiency of 85% well at the respective resonant frequencies. Similar good agreement is also found for antenna B.

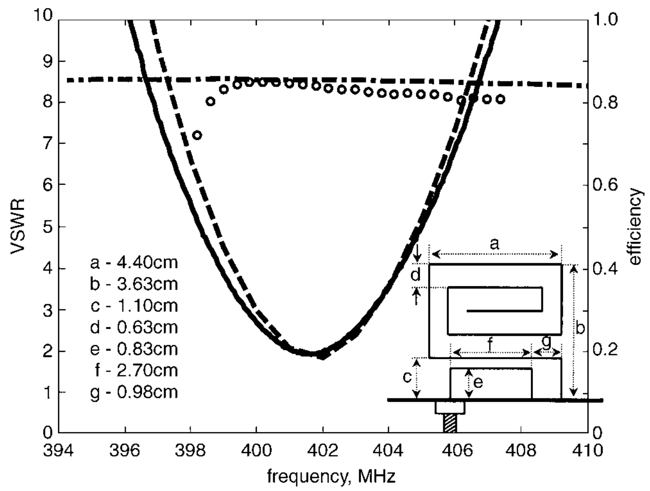

Fig. 2 *VSWR and efficiency against frequency for antenna A*

——— measured VSWR – – – simulated VSWR
– · – · simulated efficiency ○ measured efficiency

We have also explored the use of printed structures by translating the inductively coupled antenna design A to printed lines (2 mm) on 0.8 mm thick FR-4 substrate. Owing to the high dielectric constant and high loss tangent of the FR-4 substrate, the printed antenna shows a frequency shift from 400 MHz to 355 MHz, with a broader bandwidth

(2.4%) and lower efficiency (31%). Other than these observed differences, the printed antenna has characteristics consistent with wire design A. Therefore, these planar wire designs are potentially convertible into low-cost printed antennas.

Lumped element circuit model: We next propose a lumped element circuit model, as shown in the inset of Fig. 3, to explain the operation of the inductively coupled feed structure. The inductive coupling is modelled by a transformer. The input impedance of this model is given by:

$$Z_{\text{in}} = Z_{feed} + \frac{\omega^2 M^2}{Z_{body}} \tag{1}$$

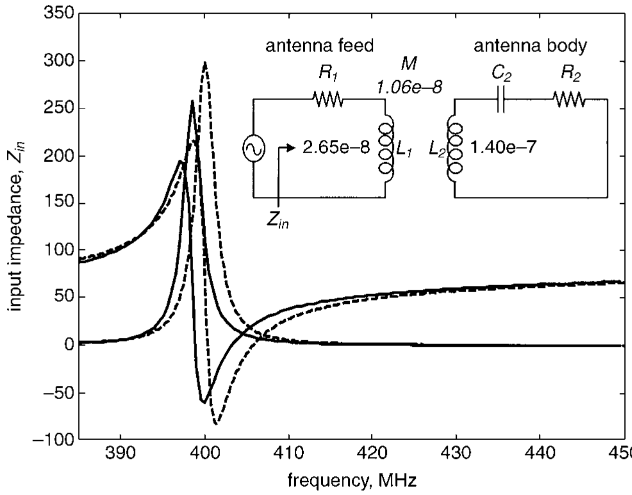

Fig. 3 *Circuit model for inductively coupled antenna and simulated input impedance of antenna A*

– – – circuit model ——— NEC simulation

To obtain the lumped element values, the antenna body and the antenna feed are simulated separately using NEC and the data are fitted to the circuit model to arrive at the *R*, *L* and *C* values. The mutual inductance, *M*, between the feed loop and the antenna body is derived analytically based on that between an infinitely long wire and a loop. Using the completed circuit model, we calculate the input impedance curves (both *R* and *X*) shown as dashed lines in Fig. 3. The solid lines in the Figure show the simulated input impedance results for the whole antenna using NEC. The results match fairly well. As we can see from (1), the transformer serves to invert and amplify the very small input resistance of the antenna body by the inductive coupling. This makes it possible for very small antennas to be matched to a 50 Ω feed line. Another important observation is that the input reactance of this antenna crosses zero at two points near the operating frequency. This higher-order tuning effect serves to increase the bandwidth of the antenna. Therefore, the inductively coupled feed achieves both input resistance step-up and bandwidth enhancement, making it an effective technique for designing very small antennas.

Conclusion: An inductively coupled feed concept has been applied to design planar, electrically small wire antennas. The Pareto GA was used to optimise the spiral winding and feed configurations by taking into account of antenna size, bandwidth and efficiency. Using the inductively coupled design we achieved working antennas in the size range $0.2 < k_r < 0.6$. The prototypes of the designs were built and measured, and the results agreed well with simulation. The wire designs were also translated to printed structures on FR-4 substrate. Other than the expected shift in the resonant frequency, the printed antennas exhibited characteristics similar to the wire designs. A simple lumped-element circuit model was also proposed to explain how the inductively coupled feed simultaneously achieves input resistance step-up and bandwidth enhancement of the antenna.

Acknowledgments: This work is supported by the Office of Naval Research under Contract No. N00014-01-1-0234 and the Texas Higher Education Coordinating Board under the Texas Advanced Technology Program.

26 August 2003

Electronics Letters Online No: 20031051

DOI: 10.1049/el:20031051

H. Choo and H. Ling (*Department of Electrical and Computer Engineering, The University Texas at Austin, Austin, TX 78712-1024, USA*)

E-mail: hschoo@ece.utexas.edu

H. Choo: Currently with the School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea

References

1 ALTSHULER, E.E.: 'Electrically small self-resonant wire antennas optimized using a genetic algorithm', *IEEE Trans. Antennas Propagat.*, 2002, **50**, pp. 297–300

2 CHOO, H., ROGERS, R., and LING, H.: 'Design of electrically small wire antennas using a Pareto genetic algorithm', *IEEE Trans. Antennas Propagat.*, 2003

3 BURKE, G.J., Lawrence Livermore Laboratory and POGGIO, A.J.: 'Numerical Electromagnetics Code (NEC)-Method of Moments', 1981

4 GOLDBERG, D.: 'Genetic Algorithms in Search, Optimization and Machine Learning' (Addison Wesley, Reading, MA, 1989)

5 CHOO, H., and LING, H.: 'Design of planar, electrically small antennas with inductively coupled feed using a genetic algorithm'. IEEE Antennas Propagat. Soc. Int. Symp. Dig., Columbus, OH, June 2003, pp. 300–303

6 MCLEAN, J.S.: 'A re-examination of the fundamental limits on the radiation Q of electrically small antennas', *IEEE Trans. Antennas Propagat.*, 1996, **44**, pp. 672–676

7 FOLTZ, H.D., MCLEAN, J.S., and CROOK, G.: 'Disk-loaded monopoles with parallel strip elements', *IEEE Trans. Antennas Propagat.*, 1998, **46**, pp. 1894–1896

8 WHEELER, H.A.: 'The radiansphere around a small antenna', *Proc. IRE*, 1959, **47**, pp. 1325–1331