Megahertz magneto-inductive waveguide for electromagnetic energy transmission in radio-frequency identification system

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Abstract: Achieving low-frequency waveguide structures that operate in the low-frequency (LF) band or megahertz range is challenging because of the long wavelengths involved. In this work, we propose a domino-structured magneto-inductive waveguide for electromagnetic energy transmission in radio-frequency identification (RFID) systems at frequencies as low as 13.56 MHz. It is implemented using a metastructure based on a domino-arranged split ring resonator (SRR). Lumped components are introduced into each SRR ring that significantly reduce the ring resonant frequencies. An analytical energy transfer model is proposed based on inductive coupling because almost all the energy is transmitted through the magnetic field. Transmission coefficient measurements were carried out and the experimental results agree well with the energy transfer model. The proposed structure has a wide transmission bandwidth that is typically 30% to 80% of the center frequency. This bandwidth is sufficient to cover the entire 13.56 MHz industry-science-medical (ISM) band and is thus suitable for energy transmission for RFID systems. The waveguide has wide application potential that may be used to extend RFID reader sensing distances or split near-field RFID electromagnetic energies in multi-point applications.

Keywords: waveguide, meta-structure, RFID

Classification: Microwave and millimeter-wave devices, circuits, and modules
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1 Introduction

Waveguides are hollow metal pipes that serve as orientation structures for electromagnetic (EM) wave propagation and are widely used for short-distance trans-
mission of electromagnetic energy in the microwave band [1, 2, 3]. The cut-off frequency of a specific waveguide is determined by its size and the permittivity $\varepsilon$ and permeability $\mu$ of the waveguide filling materials. For example, the cut-off frequency of a circular waveguide is given by [4]:

$$f_c = \frac{1.8412}{2\pi r} \sqrt{\frac{\mu}{\varepsilon}}$$

(1)

Where $r$ is the radius of the waveguide section. The typical cut-off frequency of a centimeter-sized hollow waveguide is above the gigahertz (GHz) level and EM waves at frequencies below the cut-off frequency cannot propagate in such a waveguide. Extending the cut-off frequency of a waveguide downwards requires used of a larger waveguide size or a filling material with higher $\varepsilon$ and $\mu$. However, it remains difficult to reduce the waveguide cut-off frequency to the megahertz (MHz) range. Because of the restrictions imposed by the limited $\varepsilon$ and $\mu$ ranges of conventional filling materials (their product is usually no more than 1000 [5]), the dimensions of megahertz waveguides would need to have magnitudes of several meters, which would either be difficult to fabricate or impractical for actual use.

In the case where the waveguide has an operating frequency band that covers the MHz range and the structure is of an acceptable size, many novel applications can be realized. One example is that such a low-frequency (LF) waveguide can be used to extend the sensing distance of a radio-frequency identification (RFID) reader or split a single near-field RFID electromagnetic signal for insertion into a multi-point reader [6]. Furthermore, with appropriate matching, the MHz waveguide would able to receive and transmit LF electromagnetic waves directly, which could contribute to the realization of a new form of compact RFID antenna in the 13.56 MHz industry-science-medical (ISM) band.

Metamaterials are artificial materials with subwavelength cell structures that are arranged in periodic arrays and these materials have unnatural permeability and permittivity properties [7]. Based on these extraordinary dielectric properties, metamaterials would exhibit a large $\varepsilon \times \mu$ product (where both of these properties could have negative values) or produce some new transmission behavior, which may be helpful when scaling down the dimensions of LF waveguides, e.g., for use as thin-film magneto-inductive cables [8, 9]. The unnatural electromagnetic properties of metamaterials are usually achieved using resonant structures such as the split ring resonator (SRR) and its variants [10, 11, 12]. This resonance is caused by the inductance and capacitance distributions in each cell. Because the distributed capacitance of the SRR cell is of the order of a few picofarads, the diameter of an SRR structure-based cell would still be unacceptable when operating in the MHz range. Additionally, SRR units are high-quality-factor resonance loops with narrow pass bands, which are thus unsuitable for use with waveguides that require broadband transmission characteristics.

Recently, numerous efforts have been devoted to increasing the wavelength-to-cell size ratio to achieve a better homogenization. Proposed designs have included a multi-turn spiral resonator unit [13] and introduction of a lumped capacitor or inductance element into each unit cell [14, 15].
Inspired by these efforts, we propose a compact-size low-frequency waveguide for RFID energy transmission. This waveguide structure is implemented by introducing a lumped capacitor into an SRR structure to obtain a resonance frequency that is as low as ~10 MHz, and a wide transmission bandwidth is also achieved because the introduction of the capacitance reduces the quality factor of the waveguide.

2 Design of the domino-structured metamaterial

The geometric structures of the proposed unit cell and the manufactured resonator array are illustrated in Fig. 1(a) and Fig. 1(b), respectively. As shown in Fig. 1(a), each unit cell consists of a loop coil and several parallel chip capacitors. The coil can be treated as an inductance while the whole unit cell can be regarded as being equivalent to a series resonance loop.

![Image](image-url)

Fig. 1. (a) Geometric structure of unit cell. (b) Structure of assembled domino metamaterial waveguide. (c) Photograph of unit cell. (d) Photograph of assembled domino metamaterial waveguide.

The single-turn copper loop is printed on the top layer of a printed circuit board with an inner radius of 70 mm and strip width of 2.54 mm, and the copper wire thickness is 0.035 mm. While a metamaterial is used to enhance the field strength between the antennas, it will also introduce an insertion loss. Therefore, low-loss ceramic capacitors are introduced to minimize the extra losses produced by the metamaterial. The fabricated cell has dimensions of 74 mm × 95 mm and the unit cell dimensions could be reduced if multi-turn coils are used. Five via holes are opened on the substrate layer of each unit cell to fix the cells into the pipe structure. Fig. 1(b) shows the domino structure produced by assembling multiple unit cells. These planar resonators are aligned to allow them to be set up in a tube with their planes oriented perpendicular to the axis of propagation. There is a regular and variable gap denoted by a between the cells and a periodic array is constructed.
In the near field, the magnetic and electric fields are mostly decoupled, and the proposed metamaterial is used to cause the magnetic field to converge. A time-varying magnetic field can be generated using the power supply in the antenna and the magnetic flux generated by the alternating current will link with the other coils in the array. The alternating changes between the magnetic field and the induced current result in a propagating wave and energy is transferred via coupling between the coils of the unit cells. An inexpensive flame-retardant (FR4) material is thus chosen as the substrate material because its magnetic losses are negligible.

3 Analysis of the domino structure

3.1 General circuit model of domino-structured resonators

The transmission and reflection coefficients $S_{21}$ and $S_{11}$, respectively, are used to evaluate the performance of the proposed waveguides. For analysis of the wideband performance of the proposed domino waveguide structure, a pair of unmatched loop antennas is used. For simplicity in analysis of the proposed system, each antenna was identical to the loop coil contained in each unit cell. The equivalent circuit of the waveguide, which consists of $n$ resonators and a pair of antennas, is shown in Fig. 2.

![Fig. 2. Schematic of system composed of $n$ resonators and a pair of unmatched antennas.](image)

In our proposed domino waveguide application, the gap between the adjacent resonators is relatively small and is much smaller than the radius of the loop coil $r$ (the ratio of $d/r$ would exceed 10). Under these conditions, the coupling between every pair of coils must be considered to create a concise model. The overall system can be treated as a multiple-mode resonator array. The transmitter is a loop coil driven using an AC voltage power supply $V_S$ operating at a frequency $\omega$, where $L$ is the equivalent inductance of the coil, $R_S$ is the equivalent series resistance (ESR) of the power supply, and $R_L$ is the total ohmic loss of the coil and involves the ESR and the radiation resistance loss. Periodic unit cells are configured as series resistor-inductor-capacitor (RLC) resonators, where $C$ is the compensating capacitance of the resonator, and $R_C$ is the ESR of the capacitance. Given the interchangeability of the transmitters and receivers here, the parameters of the transmitter are accordingly the same as those of receivers, which simplifies the analysis further. $R_{\text{Load}}$ is the load resistance of the overall system.
According to Kirchhoff’s voltage law, the general circuit equation of the domino system can be formulated as follows:

\[
\begin{bmatrix}
Z_{\text{transmitter}} & j\omega M_{12} & \cdots & j\omega M_{1(n+1)} & j\omega M_{1(n+2)} \\
 j\omega M_{12} & Z_{\text{resonator}} & \cdots & j\omega M_{2(n+2)} & j\omega M_{2(n+2)} \\
 j\omega M_{13} & j\omega M_{23} & \cdots & j\omega M_{3(n+1)} & j\omega M_{3(n+2)} \\
 \vdots & \vdots & \ddots & \vdots & \vdots \\
 j\omega M_{1(n+2)} & j\omega M_{2(n+2)} & \cdots & j\omega M_{(n+1)(n+2)} & Z_{\text{receiver}}
\end{bmatrix} \cdot \begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
\vdots \\
I_{n+2}
\end{bmatrix} = \begin{bmatrix}
V_s \\
0 \\
0 \\
\vdots \\
0
\end{bmatrix}
\] (2)

where \(Z_{\text{transmitter}}\), \(Z_{\text{receiver}}\) and \(Z_{\text{resonator}}\) represent the loop impedances of the transmitter, the receiver and the resonators, respectively; \(M_{ij}\) is the mutual inductance between coil \(i\) and coil \(j\); and \(I_i\) is the current in winding \(i\).

Assuming that the resonance frequency for all unit cells is tuned to the same value, then the transmission coefficient \(S_{21}\) can be expressed as:

\[
S_{21} = \frac{|I_{n+2}|R_{\text{Load}}}{V_s}
\] (6)

All values of \(I_i\) in Eq. (2) can be obtained by working them out using Eqs. (3), (4) and (5). Therefore, the transmission coefficient could then be formulated as a function of the mutual inductance \(M_{ij}\), the load resistor \(R_{\text{Load}}\) and the operation frequency \(\omega\), as shown in Eq. (7) below, because the resistance of each loop is omitted.

\[
S_{21} = f(M_{12}, M_{13}, \ldots, M_{(n+1)(n+2)}, M_{(n+2)(n+2)}, R_{\text{Load}}, \omega)
\] (7)

However, the method used to calculate the mutual inductances of the coaxial coils should be explored before the transmission coefficient \(S_{21}\) is estimated.

### 3.2 Mutual inductance of coaxial coils

Because the coil’s strip width can be ignored when compared with its radius, the single-turn coil can be regarded as a filamentary coil. The discussion of the mutual inductance \(M\) of two coaxial filamentary coil loops can be traced back to 1950 and the following simple formula was derived [16].

\[
M = \mu_0 \sqrt{\frac{r_1 r_2}{g}} \left(2 - g^2\right)K(g) - 2E(g)
\] (8)

where \(\mu_0\) is the magnetic permeability in a vacuum, which is equal to \(4\pi \times 10^{-7}\) H/m. \(K(g)\) and \(E(g)\) are the complete elliptic integrals of first and second kinds, respectively. In addition, \(g\) is formulated as:

\[
g = \sqrt{\frac{4r_1 r_2}{d^2 + (r_1 + r_2)^2}}
\] (9)

where \(r_1\) and \(r_2\) are the radii of the two coils. \(d\) represents the distance between the two coaxial coils, as shown in Fig. 3. We also present the mutual inductance
characteristics versus axial distance $d$ that were determined using the analytical method, as shown in Fig. 4.

$$\Gamma = S_{12} = f(d_{ij}, d_{23}, \ldots, d_{(n-1)n}, R_{Load}, \omega)$$

(10)

The bandwidth and the center frequency of the domino-structured waveguide can be acquired because $S_{21}$ is given. It should be emphasized here that a general model of the domino-structured resonator array is proposed in this paper. However, because of the complexity of the cross-coupling that occurs between all unit cells, it is difficult to derive a simplified analytical equation.

4 Verification of domino-structured waveguide

4.1 Experiment setup

Several experiments were performed to verify the numerical analysis results for our LF domino waveguide with the practical resonator array. The experiments mainly focused on the transmission coefficient $S_{21}$ of the proposed waveguide.

The cells were tuned to a resonance frequency of 13.71 MHz by soldering five $100 \text{ pF}$ multilayer ceramic capacitors together with a $4–75 \text{ pF}$ variable trimmer capacitor. Use of the five parallel ceramic capacitors is intended to reduce the ESR of the cells and also reduce the resonance losses. In addition, the resonance frequencies of all cells are tuned to be exactly the same by adjusting the variable capacitor. There are five nylon screws used to fix the neighboring cells together to construct an equal-arrangement domino waveguide tube. The unit cell parameters are as shown in Table I.
The prototype waveguide is designed to extend the detection distance of an RFID card reader that operates at 13.56 MHz. The induction distance is increased from 4 cm to 22 cm when the waveguide is attached to the RFID card reader. The prototype is assembled using 20 resonator cells with a spacing interval of 1 cm. In addition, the transmission distance could be extended further if both the assignment density and the number of cells of the waveguide increase.

The RFID card reader is only used at specific sets of distance and operating frequency, while the discussion in Section 3 applies to the general situation. Additionally, the proposed metamaterial demonstrated a wide operating bandwidth when the lumped elements were introduced. Therefore, a pair of unmatched loops is used as the wideband magnetic antenna to test the $S_{21}$ value of the proposed domino waveguide versus change in frequency. The test connections and the equivalent circuit are shown in Fig. 5 below.

Two experiments were carried out to verify the $|S_{21}|$ of the proposed domino-structured waveguide. The first test was performed to investigate the transmission coefficient and to verify the accuracy of the proposed domino-structured waveguide model. The second test determines the transmission bandwidth by comparing the variations in $|S_{21}|$ with the numbers and assignment intervals of the unit cells.

### 4.2 Transmission coefficient of domino-structured waveguide

The transmission coefficient $|S_{21}|$ is measured to verify the accuracy of the proposed analytical model of the LF waveguide. The spacing between the adjacent resonators and antennas is set at 10 mm, as shown in Fig. 5. Testing was performed using five resonators and fifteen resonators separately, and the transmission coefficient was measured $|S_{21}|$ is measured over the range from 2 to 25 MHz with and without the waveguide by an RF signal analyzer (Agilent-N9912A). Two-port

| Table I. Circular resonator parameters |
|----------------------------------------|
| Radius of resonator | 35 mm |
| Turns of coil | 1 |
| Inductance (L) | 220.8 nH |
| Capacitance (C) | 550.3 pF |
| Self-resonance frequency | 13.71 MHz |
| Equivalent series resistance (at 13.71 MHz) | 0.44 Ω |
| Quality factor (Q) | 45.5 |

![Fig. 5](image-url) Test configuration for the proposed LF waveguide and the equivalent circuit of the overall system.

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open-short-load-through calibration is performed with two 1 m RG58 cables. In the experiment, the output power is set as $-10$ dBm. Based on the parameters given in Table I and the general model formulation of Eq. (2), curves of the measured and calculated $|S_{21}|$ characteristics are presented as a demonstration of the accuracy of the proposed model.

The curves in Fig. 6(a), (b) and (c) show the transmission performance of waveguides composed of five, ten and fifteen units, cells respectively, and the spacings between the antennas are 6.9 cm, 12.7 cm and 18.5 cm in these cases. Additionally, $|S_{21}|$ is measured without waveguide for reference using antennas placed 18.5 cm apart, which is approx. $-70$ dB.

The calculated results based on the general model of Eq. (2) and the parameters shown in Table I are nearly consistent with the measured results. The errors between the measured and calculated results are in the range between 1.8 dB and 3.3 dB within the operating bandwidth, as depicted in Fig. 6(a) and (b), respectively. When the lumped capacitor values of the resonators are carefully adjusted, their parameters are shown to be within a relatively small tolerance of 1.5%. The

![Graph](a)

![Graph](b)

![Graph](c)

**Fig. 6.** Comparison of measured and calculated transmission coefficient $|S_{21}|$ of the domino system. Results for waveguides assembled with five, ten and fifteen unit cells are shown in (a), (b) and (c). (a) Five resonators; (b) ten resonators; (c) fifteen resonators.
resonators could therefore be regarded as being identical, which would match the theoretical analysis conditions in Section 3. Therefore, the calculated curves conform closely with the measured curves.

The waveguide loss is increased because lumped capacitors and unmatched antennas have been used and the peak of the transmission curve is at $-14.7$ dB, as shown in Fig. 6(c). However, when compared with the $|S_{21}|$ characteristics measured without the waveguide, an increment of nearly 55.6 dB occurs in the operating band of the domino system and the $|S_{21}|$ of the domino system would increase dramatically if matched antennas were used. It is worth noticing that the increment in the loss implies reduction of the quality factor, which would ultimately extend the bandwidth of the waveguide. To evaluate the bandwidth of the rippled spectrum of the waveguide, 20 dB attenuation was set as a threshold value and the operating bandwidth of the domino system would then exceed 7 MHz, where the bandwidth is comparable with the center frequency of the waveguide. Additionally, we predict that this phenomenon could be extended to higher frequency bands (e.g., the GHz band). Low-cost components were used to fabricate the prototype and the transmission performance could be verified if low-loss components were introduced.

### 4.3 Bandwidth of the domino-structured waveguide

In the second phase of the experiments, tests were conducted by adjusting the number of integrated resonators and the intervals between adjacent resonators in the waveguide; the transmission bandwidth characteristics were then obtained and analyzed.

Fig. 7 plots the center and cut-off frequencies of the waveguide versus variations in the number of unit cells, where the spacing between cells is 10 mm.

It is shown that the center frequency and the operating bandwidth of the domino structure would migrate to a slightly lower frequency (within 8%) as the number of resonators increased gradually from 5 to 25. This migration occurs because the attenuation slope of transition band of the waveguide is lifted with increasing numbers of resonators. Furthermore, the bandwidth would approach a constant value if the number of cells continued to increase. In addition, the transmission spectrum becomes smoother with increasing numbers of resonators as indicated by comparison of Fig. 6(a), (b) and (c). However, power consumption in the resonators also rises.

![Fig. 7. Trends of center and cut-off frequency with variations in the number of resonators used.](image-url)
Fig. 8 plots the center and cut-off frequencies of the waveguide versus variation of the spacing of the unit cells when the number of resonators used is 10.

In Fig. 8, the operating bandwidth of the waveguide was varied from 4.5 MHz to 11.1 MHz while the center frequency remained unchanged. As the interval between cells decreases, the coupling coefficient between resonators becomes larger and thus increases the waveguide bandwidth. Even the lowest bandwidth still exceeds 30% of the center frequency, which represents a broadband low-frequency waveguide. This bandwidth is sufficient to cover the entire 13.56 MHz ISM band and is therefore suitable for RFID signal transmission. Its potential applications are very wide ranging; for example, the waveguide can be integrated inside the medium to extend the transmission distance of the RFID signals.

5 Discussion and conclusions

In this work, we have proposed a compact domino-structured LF waveguide operating in the MHz range that is implemented based on an SRR with a lumped capacitor. Because chip capacitors are used in the inductor-capacitor (L-C) resonance loop, the electric field is closed and almost all the energy is exchanged via inductive coupling. The transmission model is analyzed precisely using loosely-coupled inductance theory. The transmission parameters of the proposed metastructures were measured and the results were in good agreement with the theory.

The proposed structure exhibits a wide transmission bandwidth (from 30% to 80% of the center frequency), which is caused by two factors. One factor is that the lumped capacitance that is introduced is far larger than the inductance, which reduces the quality factor of a single resonance loop; in contrast it broadens the bandwidth of each resonant ring. The other factor is that the proposed one-dimensional metamaterial forms a multi-mode resonant cavity, which then further expands the transmission bandwidth of the entire domino structure.

The center frequency is largely determined by the individual resonance loop, and specifically by the inductance of the resonant ring and the capacitance that is introduced, while the bandwidth of the entire transmission structure is determined by the density of the resonant rings. Both the center frequency and the bandwidth...
are almost irrelevant to the transmission length characteristics, which is very similar to the characteristics of a conventional high-frequency waveguide structure.

At present, the transmission loss of the proposed domino structure is approximately 10 dB or more at a distance of 20 cm, which is larger than that of traditional waveguides. This is mainly because of the losses of the lumped components themselves. However, when compared with the LF near-field free-space attenuation, the additional transmission gain obtained is still considerable (typically more than +50 dB at 20 cm). Additionally, we believe that the transmission loss can be reduced further by choosing low-loss components.

One possible application of this structure is to extension of the read/write distances of RFID systems because the electromagnetic energy can be transmitted through this symmetrical structure in both directions. The domino structure transmits energy based on inductive coupling, while the planar arranged rings can also transfer energy through their mutual inductances. The one-dimensional domino structure can also be modified further into a 2D planar structure and embedded on desktops or other surfaces to expand the sensing areas of RFID readers.

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