New Way of Generating Electromagnetic Waves

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Abstract—This article presents a new method for generating low-frequency electromagnetic waves for navigation and communication in challenging environments, such as underwater and underground. The key concept is to disturb the magnetic energy stored around a permanent magnet in a time-variant fashion. The magnetic reluctance of the medium around the permanent magnet is modulated to alter the magnetic flux intensity and direction (disturb the stored energy) in order to achieve this goal. The nonlinear properties of the surrounding magnetic material are a critical phenomenon for efficient and effective modulation. Since the proposed way of generating the electromagnetic field is not based on a second-order system (resonant structure), the bandwidth of any modulation schema is not limited to the overall system quality factor. A transmitter is prototyped as a proof of concept, and the generated field is measured. Compared with the rotating magnet, the prototyped transmitter can modulate up to 50% of the permanent magnet’s stored energy with much lower power consumption.

Index Terms—Magnetic energy, magnetic material, underwater communication, very low frequency (VLF).

I. INTRODUCTION

WIRELESS technology has been evolving to respond to the increasing demand for radios with higher data rates (bandwidth) and smaller dimensions. The only way to accomplish these two objectives simultaneously was to increase the operating frequency due to certain physical limitations. In many applications, however, an increasing frequency may not be desired. Communication under seawater or other challenging RF environment requires very-low-frequency (VLF) or ultralow-frequency (ULF) signals to penetrate lossy media that block high-frequency signals. Furthermore, new developments in neuroscience have shown the potentials of VLF and ULF electromagnetic (EM) waves to treat neurological conditions, such as Alzheimer’s disease, amyotrophic lateral sclerosis, epilepsy, stroke-related illness, schizophrenia, and traumatic brain injury. The main challenge is that most VLF and ULF generators are large and power-hungry, making them impractical or hard to use.

The reactive near field of an antenna is more critical for VLF and ULF bands than the radiated field, as the Fresnel zone may be beyond the communication link. Also, conventional electrically small antenna (ESA) design approaches are based on the linear time-invariant (LTI) systems and are bound to the fundamental limits of antennas [1], [2]. Their bandwidth and radiation efficiency are, therefore, small: a 1-m lossless antenna resonant at 1 kHz (λ = 300 km) has a bandwidth of 10^{-11} Hz (minimum Q of 10^{14}). Bandwidth can be increased by sacrificing the antenna efficiency. As a result, utilization of nonlinear and/or time-variant (non-LTI) antennas has received more interest as an alternative solution, which is not bound to fundamental limits of antennas [3]. Recent methods using permanent magnets or multiferroic materials have been proposed to provide innovative solutions that can revolutionize VLF and ULF communication.

The Alexanderson alternator, a mechanical structure based on a rotating permanent magnet, successfully implemented a permanent magnet in a transmitter in 1904 [4]. This transmitter was introduced to replace first-generation transmitters using spark-gap oscillators and was used for two decades before becoming obsolete due to the advancement of vacuum tube transmitters in the 1920s. Several variants of the Alexanderson alternator have been suggested after more than a century [5]–[11], in response to a DARPA call for VLF and ULF sources [12] in recent years. These structures intend to generate a dynamic magnetic field by modulating the spinning magnet, such as mechanical frequency modulation [8], [10], electromechanical modulation [5], mechanical shutter [9], and electrically modulated reluctance [6]. The latter design utilized electrically altering the permeability of the surrounding shield to modulate the field amplitude of a rotating magnet, instead of changing the rotational speed of the magnet in other designs. However, such mechanical generators (mechtenna) still have the same shortcomings as the original design, such as large size, massive power consumption, difficulty in modulation and transmission of information, synchronization, noise, vibration, and durability of the mechanical structure. Other mechanical vibration versions have also been proposed to generate EM waves in VLF ranges [13]–[16].

On the other hand, in 1961, the notion of acoustic resonance as a strain-powered (SP) antenna was introduced by an analysis of EM radiation from the acoustically driven ferromagnetic yttrium iron garnet sphere (YIG). Recent studies have shown that in a device with smaller physical dimensions than the EM wavelength, multiferroic antennas can take advantage of acoustic resonance to reduce antenna size [17]–[19]. As a contrast to rotating permanent magnets, strain-coupled piezoelectric and magnetostrictive composites are thus used in magnetostrictive materials to control magnetic spin states [20]–[22]. Although this technique eliminates the necessary...
inertial force in mechatenna, it faces challenges due to the matching rigidity between piezoelectric and magnetostrictive (i.e., low energy transfer from piezoelectric to magnetostrictive) and the inefficient power transfer to electromagnetic radiation. Making this structure in bulk is also a significant challenge.

This article presents an alternative approach to using magnetic material to manipulate the magnetic flux of a permanent magnet. The idea is to modify the reluctance of the flux path by pushing the magnetic flux to take an alternative path to make it time-variant. This concept is based on “variable material” rather than “variable structure” as in mechanical rotation. We take advantage of a permanent magnet, equivalent to a lossless electromagnet with a superconductor winding, to produce a static magnetic flux without dissipating power. Meanwhile, we alternate the direction of this flux between free space and a medium with high permeability. The permeability of the magnetic material near the permanent magnet varies by adjusting the current through a control coil, depending on the B–H curve of the magnetic material [6].

This article is organized as follows. The theoretical basis for the proposed transmitter is described in Section II. Section III introduces the design of the prototyped system. Section IV is devoted to the measurement and simulation results and evaluation of the proposed system among low-frequency antennas, and this article is concluded in Section V.

II. THEORETICAL BASIS

Based on Maxwell’s equations, the electric field generated by a current distribution $J(r)$ at the far zone is computed as

$$\mathbf{A}(r) = \frac{\mu_0 e^{-jk} r}{4\pi r} \int J(r') e^{-jk r'} d\nu'$$

$$\mathbf{E}(r) = -j\omega(\mathbf{A}_\theta + A_\phi \hat{\phi}).$$

(1)

For small volume (ESA case), the magnitude of the current, $J(r)$, must increase significantly, while a large integration volume of coherent argument, $J(r') e^{-jk r'}$, (large antennas or arrays) will produce an appropriate electric field at the far zone. The most common way to produce electromagnetic waves in a limited volume relies on a time-variant current in a resonant structure. Stored energy alternates between electric and magnetic forms, which are periodically stored in two different parts of the radiating system. Any or both types of stored energy leak energy in the form of radiation. Thus, there is a specific amount of radiated power, $P_r$, for a maximum amount of stored energy, $W_{\text{max}}$. Moreover, the fundamental limits of the antennas [1], [2] link the electrical size of the antenna (maximum dimension of the antenna divided by the wavelength) to $Q = \omega W_{\text{max}} / P_r$ (quality factor of the antenna). Designated ESAs would have low radiation efficiency (large current in a small volume) and small bandwidth (high Q-factor) [23]. However, bandwidth can be increased by sacrificing the radiation efficiency. Consequently, one must use nonlinear and/or time-variant (non-LTI) antennas to overcome the fundamental limits of antennas [3]. It is still vital to address the issue of the large current density for ESAs.

Because of the aligned spins of unpaired electrons, permanent magnets produce static magnetic fields by their equivalent bound currents. The static magnetic potential, $\mathbf{A}(r)$, for a magnetized medium, $\mathbf{M}(r)$, is computed [24] as

$$\mathbf{A}(r) = \frac{\mu_0}{4\pi} \int \frac{1}{r} \nabla' \times \mathbf{M}(r') d\nu' + \frac{\mu_0}{4\pi} \int \frac{1}{r} \left[ \mathbf{M}(r') \times \hat{n} \right] d\nu'.$$

(2)

For a uniform magnetization, the volume integral vanishes, and the magnetic potential is the result of the surface integration of the current $J_s(r) = \mathbf{M}(r) \times \hat{n}$. For example, consider a permanent magnet with 1 T magnetization, which has an equivalent surface current of 797 700 A/m. The permanent magnet provides this massive current without any effort. The challenge is how to transform a permanent magnet’s static field to a dynamic field.

Let us first look at the magnetic flux density of a uniformly magnetized sphere [24], as shown in Fig. 1

$$B(r > a) = \frac{\mu_0}{4\pi} \left[ \frac{-m}{r^3} + \frac{3(m \cdot r) r^3}{r^5} \right], \quad m = \frac{4}{3} \pi a^3 M$$

(3)

where $M(A/m)$ is the magnetic dipole moment per unit volume of the permanent magnet. As is evident from the closed-form magnetic flux density of spherical magnet, there is a $1/r^3$ decay for $r > a$. One can compute the total magnetic energy stored around the magnet as

$$W_m = \frac{\mu_0 m^2}{12\pi a^3} = \frac{\mu_0}{9} V |\mathbf{M}|^2$$

(4)

where $V$ is the volume of the magnet with magnetization $\mathbf{M}$. One can compute the total energy stored outside a sphere with radius $r > a$ as

$$W_r = \left( \frac{a}{r} \right)^3 W_m.$$  

(5)

The above equations indicate that the magnetic energy contained in the radius $r$ sphere and the magnetic flux intensity at the distance $r$ decrease by $1/r^3$. Thus, to reduce the size of the transmitter, a high magnetic flux must be modulated when selecting a small $r$. Otherwise, miniaturization must be sacrificed in order to modulate smaller magnetic fluxes at larger $r$.

The first modulation approach uses a material with a controllable reluctance to create a shielding layer at radius $r$. Ideally, one can alter the shield’s reluctance from a small to substantial value. This process allows the stored energy outside the shield to be temporarily decoupled from the magnet.

![Fig. 1. Magnetic flux density decays by $1/r^3$.](image-url)
The spherical shield closes the field lines that pass it and dissipates the \( W_r \) energy every half cycle in the low reluctance mode. It then allows the magnet to store energy outside the shield again by increasing its reluctance. We presume that the reluctance variation does not substantially disrupt the magnetic flux within the shield for analytical convenience. There are various constraints, including loss, size, the current required to control the shielding material’s reluctance, and saturation level, which dictate the proper values for \( r \).

We consider the next approach to be an asymmetric system consisting of a ferrite yoke (as the variable reluctance magnetic material) and a permanent magnet (as the magnetic flux source), as shown in Fig. 2(a) and (b). Since the permanent magnet attracts the ferrite yoke, the total energy stored in this system is a function of the yoke’s distance to the magnet. We simulated this structure using ANSYS Maxwell for different materials and ranges and compared the system’s energy with the energy stored in the isolated magnet. The simulation results, as shown in Fig. 2(c), suggest that nearly half of the magnet’s energy is converted into kinetic energy when the ferrite yoke contacts the magnet, and the other half is still stored around the system. The system energy for \( D = 1 \) cm is about 90% of its maximum value, as the simulation results show. One can then move the yoke 1 cm away from the magnet back and forth and modulate the stored energy with a modulation depth of 40%. The mechanical resonance structure (i.e., a spring and a fixture) can conserve kinetic energy. We intend to modulate the reluctance, rather than a mechanical movement, to make the stored energy time-variant.

While the spherical shield offers a significant modulation depth (close to 100%), it is large and 3-D. On the other hand, the system with ferrite yoke has much smaller dimensions; however, it cannot provide a sufficiently broad modulation depth. Therefore, we combine the two methods by putting the magnet on a ferromagnetic film with a proper winding to modulate the magnetic flux by adjusting the reluctance of the film. The design parameters include the ferrite characteristics, particularly the nonlinearity of its B–H curve, the thickness of the ferromagnetic film, the topology of the structure, and the windings. The design objectives are high magnetic flux, a high modulation depth, small size, and low dissipated power. One of the tasks to achieve these objectives is to utilize the relationship between magnetic flux, \( B \), and magnetic field, \( H \), effectively.

### III. Transmitter Design

We have designed and prototyped different structures to examine our proposed approach. Fig. 3(a) shows the ANSYS model of one of our designs. The permanent magnet used in this transmitter is a rare-earth Neodymium magnet (N52, \( 6 \times 1 \times 0.5 \) cm), which is the strongest permanent magnet available in the market. Also, we used seven layers of Metglas sheets 2705 M (\( B_s = 0.77 \) T) with a total thickness of 0.178 mm as the magnetic film. A 40-turn coil around a c-shape magnetic core made of amorphous AMBC (\( B_s = 1.56 \) T) with a \( 2 \times 2 \) cm cross section generates the magnetic flux needed to modulate the magnetic film’s reluctance. We select a low reluctance core with a reasonably broad cross section to ensure that the c-shape core operates at its linear state. As a result, the current through the control coil generates a magnetic flux in the magnetic film.

Fig. 3 shows the flux density on the system for two different values for the control current. Fig. 3(b) shows that small areas of the magnetic film are in saturation when the control current is zero. The saturated film helps spread magnetic flux in the air and store magnetic energy around the magnet. The small saturated area indicates that the magnetic film operates as a barrier and closes inside the magnetic flux (closed mode). Next, we apply 0.5 A current to the control coil, and the pattern of magnetic film saturation shifts to Fig. 3(c), which means that the saturated area is larger than the closed mode. In this mode, the magnetic flux spreads more in space, and more energy is stored around the magnet. We name this state of the system “Open mode.”

This system’s operating modes will differ by adjusting the arrangement of the magnet or the magnetic film. For example, the magnetic film may be saturated by a larger magnet with zero current. The saturated area of the magnetic film can then be reduced by a magnetic flux generated by the control current against the magnet’s magnetic flux. In this case, the system’s operating modes switch to open and closed modes for zero current and high current, respectively. One can apply a sinusoidal current to the control coil to change the amount of...
Fig. 3. (a) Maxwell model of the prototyped system. Magnetic field distribution of the Metglas (b) control current is zero and the system is in closed mode and (c) control current forces the Metglas to saturation (open mode).

energy stored around the magnet periodically. Fig. 3(b) also shows that the magnetic flux density in the AMBC core is less than 0.13 T, indicating that the amorphous AMBC cross section we have is higher than what we needed to keep it out of saturation. One can use a smaller core to reduce overall system size and weight.

The proposed transmitter uses a multiphysics approach to simultaneously incorporate certain electromagnetism/magnetism concepts to demonstrate the idea’s viability and its supremacy over the standard coil. The first step is to use a permanent magnet with an intrinsic high magnetic moment that, without the need for external energy, can produce an equivalent field like a high-power consumption coil [12]. The second step is to take advantage of the nonlinear behavior of the magnet’s energy observed by the asymmetric system of Fig. 2 (to modulate the permanent magnet). The third step is to utilize the nonlinear behavior of the magnetic film (operating around the knee point of the Metglas B–H curve) to switch between its deep saturation and out-of-saturation with a minimum required power. The switching is facilitated by using the permanent magnet to bias magnetic film around its knee point. The fourth step is to modulate the magnetic film in the closed-loop structure without air gap (including the c-shape core and Metglas sheet) to deliver the necessary energy to the magnetic film while keeping the input power of the control coil and the leakage from the coil to a minimum level. Thus, the concurrent realization of these conditions leads to using the control coil as a trigger for releasing the energy stored in the permanent magnet in a time-varying nonlinear mechanism. As a result, the antenna, at the desired operating range, is designed to achieve most of its leakage from the permanent magnet’s energy, which is greater than the leakage from the control coil alone or any standard coil with the same input power.

IV. RESULTS AND DISCUSSION

A. Measured Results

Assessing the performance of the prototyped transmitter [Fig. 4(a)] is a major challenge due to the lack of a reliable and calibrated magnetometer. To address this, we use the magnetic field of a rotating permanent magnet as a reference. We also used a low-noise audio amplifier connected to an air-core search coil as a receiver. Also, the magnet used in the transmitter and the one used as the rotating magnet are identical. If the measurement setup is the same (the transmitter replaces the rotating magnet, while the relative location to the search coil is the same), we can assess our transmitter accurately. Fig. 4(b) shows the permanent magnet plastic case, which connects to a Dremel 4000 rotary tool (35 000 r/min) through its main shaft [see the inset of Fig. 4(b)]. A metal shaft is in place to secure the other end of the plastic enclosure to a solid fixture when it rotates. We were able to rotate the magnet up to 25 800 r/min (equivalent to 430 Hz). Fig. 4(c) shows the rotating magnet and the search coil with the distance $R = 1.2$ m.

Fig. 5(a) shows the measured signal at the output of the low-noise audio amplifier connected to the search coil as the rotary tool rotates the magnet. The distorted waveform is due to the nonlinearity of the detection circuitry (audio amplifier). Next, we remove the rotary system and replace it with the proposed transmitter. We used a signal generator to feed the proposed transmitter via a buffer amplifier with a 430 Hz sinusoidal waveform. In addition to the voltage waveform on the audio amplifier output, Fig. 5(b) shows the input current waveform. Comparing the two voltage waveforms in Fig. 5 is reasonable by maintaining the same receiving and measuring method for both cases. Notice that the rotating magnet switches its field polarity per half cycle (swinging between $+B(R)$ and $-B(R)$ or $2\Delta B_{\text{max}}$), while the proposed transmitter can open and close the entire magnetic flux of the magnet (swinging between 0 and $+B(R)$ or $\Delta B_t$) at its peak. Therefore, the rotating magnet produces twice as much of a time-varying magnetic flux as our proposed transmitter produces at its ideal performance. Note that the magnetic
flux maximum $\Delta B_{\text{max}}$ is equal to its static value for a given permanent magnet due to the low frequency (quasi-static), and a rotating magnet’s time-variant magnetic flux is equal to $B_{\text{max}} \cos \omega t$. From now on, we compare the transmitter’s measured time-variant flux with the permanent magnet’s static flux at the same point, and we call it modulation depth

$$\text{Modulation depth} = \frac{B_t}{B_{\text{max}}} \times 100 \, \%.$$  \hfill (6)

Measuring the total power required to generate a time-varying magnetic flux at a given distance is crucial in evaluating the transmitter’s performance. Based on the measured signal shown in Fig. 5(b), the sinusoidal voltage applied to the control coil is 0.95 V, and the current is 0.6 A, which results in an average power of 0.285 W. The modulation depth of the proposed transmitter and the rotary device can be compared with the measured input power in mind. The measured flux, shown in Fig. 5, is used to calculate the modulation depth of 51%. Note that the maximum modulation depth for the transmitter is 100%, whereas the magnet’s modulation depth is 200%. Fig. 6 also shows the measured modulation depth of the transmitter versus the input power. In this input power range, the majority of the obtained modulation depth is due to the leakage of the permanent magnet’s energy, and less than 35% of the leakage is attributable to the leakage of the control coil, which reflects the superiority of the proposed system over the standard coil. This ratio is obtained by comparing the transmitter’s leakage power to that of the control coil alone (without Metglas sheet and magnet), while the input power and measurement setup are the same.

One approach to assessing the measurement method is to measure the magnitude of the magnetic flux at various distances for a given sinusoidal drive current. Fig. 7 shows the output voltage of the receiver versus $R$. The magnetic flux (which is linearly proportional to the output voltage) decays by $1/R^3$ as expected. This figure also provides a guideline for estimating the magnitude of the time-variant magnetic flux at any distance where measured/simulated data are available at least at one point in the same direction. The theoretical
equation [25] was used to find the magnetic flux for the rotating magnet and determine the coefficient required to convert the obtained voltage into the magnetic flux.

The transmitter will, therefore, generate \( 0.17 \mu \text{T} \) at 1.2 m. In the same way, the \( 1/R^3 \) decay of the magnetic field of the antenna allows extrapolating the field at a distance of 1 km, although the magnetic flux of 1 km is too low to measure with our magnetometer. It is estimated that the magnetic flux will be 0.294 fT at 1 km. The results show that 1 fT can be accomplished at 1 km with a permanent magnet volume of 10 cm\(^3\) with a power consumption of less than 0.5 W. Also, the proposed antenna is compared with other current designs in Table I.

In terms of bandwidth and data rate, the proposed transmitter does not comply with the fundamental antenna limits. Indeed, the time-variant basis of the proposed structure gives rise to a parametric or non-LTI system that allows us to change the data transfer rate independently of the antenna quality factor. Consequently, this non-LTI system results in higher data rates being feasible. Moreover, it has shown that the stored energy frequency can be quickly shifted (FSK) without breaching the fundamental limits [26]. Therefore, the frequency of the field modulation in the proposed transmitter can be changed from a few hundred hertz to tens of kilohertz without any restriction. Besides, any modulation type, such as frequency or amplitude modulation, can be applied to the proposed transmitter.

### B. Simulation Results

We conduct further analysis in the simulation domain after verifying the transmitter’s functionality in the measurement domain. We used magnetostatic simulation in the software package, ANSYS Maxwell, to achieve that objective. In this analysis, four different cases have been simulated: 1) an isolated permanent magnet; 2) an open-mode transmitter (current on); 3) a closed-mode transmitter (current off); and 4) a deep closed-mode transmitter (reverse current on). One can use case 1 magnetic flux to examine the effects of the electric current and the magnetic film thickness on magnetic flux in cases 2 and 3. Also, the modulation depth is determined by subtracting from case 2 the magnetic flux in case 3 or 4 and dividing the result by case 1 magnetic flux. The simulation results for different cases at \( R = 0.88 \) m are shown in Fig. 8.

Fig. 8(a) shows that case 2 (open-mode transmitter) generates 54% of the flux from an isolated magnet (case 1). This value is essential as we determine the size of the magnet required for a given application. Besides, the modulation depth for cases 3 and 4 is 41% and 46%, respectively. Although we used an approximate B–H curve for the Metglas film in the simulation domain, the results are in good agreement with the measured results (51% modulation depth). Note that the drive current is a balanced sinusoidal in our measurement setup (plus and minus currents); therefore, we compare the measured results with modulation depth in case 4 as 46%.

Next, we analyze the time-domain behavior of the rotating magnet and the proposed transmitter using a transient analysis by ANSYS Maxwell. Fig. 8(b) shows the magnetic flux of the rotating magnet at \( R = 0.88 \) m. As we expected for a quasi-static case, the maximum value of the flux is equal to the magnetic flux of the static magnet at the same distance \( R = 0.88 \) m. The same behavior is observed for the proposed transmitter for two different drive currents.

We have also analyzed the effect of the magnetic film thickness on the transmitter performance. The Metglas film available comes in a roll, with a thickness of 10 mil (0.0254 mm). The thickness of the magnetic film can, therefore, vary from one layer to an integer number of layers \( n \times 10 \) mil. Fig. 9

![Fig. 7. Measured field versus range. The data points show each individual measurement, and the line is the result of curve fitting.](image-url)
Fig. 8. Simulation results. (a) Magnitude of the magnetic flux at 0.88 m away from the magnet in the magnetostatic solver, (b) time-domain solution of the rotating magnet, and (c) time-domain solution of the transmitter in the transient solver, for two different control currents.

Fig. 9. Effect of the number of layers in modulation depth, when 0.5 and 0.7 A are applied as input control current.

shows the simulation results for a variety of Metglas layers used in the magnetic film for two different drive currents. The optimal number of layers for drive current of 500 and 700 mA is 7 and 8, respectively. Therefore, to build the magnetic film, one has to know the drive current in addition to the magnetic material’s B–H curve.

C. Comparison Among Low-Frequency Antennas

Many articles have been published in the last three years on ULF antennas; however, most of them have not evaluated their work with a concrete criterion. Therefore, the performances of these proposed antennas are difficult to assess and compare. We consider a permanent magnet’s magnetic flux to be a suitable reference to evaluate the performance of any ULF transmitter. Hence, we believe the field produced by a rotating magnet to be a reference to assess the field generated by any technique with a magnet of the same volume. In this way, we calibrate the receiving device (searching coil or any other type of magnetometer), specifically if we can rotate the magnet to the generator’s operating frequency. Also, we suggest calculating the leakage of the windings around the ferrite cores independently of the permanent magnet to distinguish between the permanent magnet’s contributions and the entire field of windings.

In this research, the magnetic flux per volume of selected published designs is compared in Table I to give a better estimate of the performance of our design. Note that most articles do not provide details about the antenna’s total volume, and the information is limited to the size of the main radiating element. This comparison aims to determine the minimum volume needed to reach a field strength of 1 fT at 1 km.

As shown in Table I, the results for the transmitter/source volume of 1 cm$^3$ ($\Delta B/Vrad$) show that the rotating magnet has the maximum magnetic flux as expected. Without any modulation, the rotating magnet generates a magnetic flux of about $200 \times 10^{-3}$ fT/cm$^3$, whereas any designs aimed at modulating magnet rotation reduced its efficiency significantly. The best multiferroic antenna design in the literature, which can generate a magnetic flux of approximately $13.3 \times 10^{-3}$ fT/cm$^3$, is also far from competing with the rotating magnet. Our proposed transmitter can generate a $98 \times 10^{-3}$ magnetic flux, making it a feasible candidate to compete with the rotating magnet.

V. Conclusion

A new method for generating electromagnetic waves using the permanent magnet’s static magnetic flux has been introduced. By using reluctance modulation, the direction of the magnetic flux and the location of the stored magnetic energy have been changed to create a time-variant field. A method for evaluating a ULF transmitter’s performance has also been implemented and used to assess the proposed transmitter. It has been shown that the prototyped transmitter produces a time-variant field with a modulation depth of 50%. While we have not tried to minimize the size and weight of the transmitter, it has reasonable dimensions and weight. We also analyzed the power consumption of the transmitter and the calculated results. The calculations show that we can generate 1 fT of time-variant magnetic flux at 1 km using a magnet volume of 10 cm$^3$. The proposed transmitter is a viable
candidate to compete with the rotating magnet to generate the EM waves in various VLF and ULF applications in a compact and low-power fashion.

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