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Novel layout of a bi-metallic nanoring for magnetic field pulse generation from light

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Abstract

Recently Tsiatmas et al proposed using a nanoring made of two different metallic sectors to generate a magnetic pulse from a laser pulse [1]. Non-uniform heating of the ring creates very large temperature gradients, which drive thermoelectric currents, and this creates a localized magnetic field. However, heat from the laser pulse may result in the melting of the nanoring. We propose a symmetric structure made of four metallic sectors, which results in a higher magnetic field generation together with a lower lattice temperature. We also show that the magnetic field depends strongly on the size of the metallic sectors and interpret the results with the help of the electromotive forces, the overall ring resistance, and Biot–Savart law.

1. Introduction

Ultrashort magnetic pulses enable fundamental studies of magnetic switching, which underlies much of the data storage industry as well as the emerging field of spin logic. High magnetic field confinement is also essential to sustain the increase in data storage density. It is anticipated that a confined magnetic field combined with laser light, preferably in pulsed form [2], will bring the magnetic recording technology to multi Tb in$^{-2}$ areal densities. Moreover, confined magnetic fields may find applications in new schemes targeting nanoscale magnetic resonance imaging [3, 4].

Although the generation of ultrashort magnetic pulses has been addressed for several decades, it remains very challenging. Relativistic electron bunches [5] have proven effective but the need for electron accelerators has limited their use. Alternative techniques based on the inverse-Faraday effect and on the optically-induced spin–orbit coupling effect rely on pulses of light to generate ultrafast magnetic pulses [6–8]. They are limited to a few material systems and are not amenable to strong spatial confinement of the magnetic field.

Another approach is to use a ring structure in which ohmic or displacement currents can be driven by light. This is the approach taken in ‘split-rings’, the emblematic structures first proposed as building blocks for metamaterials [9]. It was later calculated that a magnetic field resulting from an ohmic current could be generated in a properly dimensioned metallic ring when the incident wave and the polarization directions are both parallel to the plane of the ring [10]. Recently a design based on a corrugated ring was also proposed as a concentrator of magnetic field from light [11]. However, in all these cases the magnetic field oscillates at the frequency of the incident light.

Modifying the ring to include two metallic junctions has been proposed in order to generate a steadier magnetic field. This design is reminiscent of the setup used by Seebeck in 1821 for the discovery of the now eponymous effect. Originally Seebeck coined this effect thermomagnetism [12, 13]. Shortly afterwards, Oersted pointed out that it would be better named the thermoelectric effect. For this discovery Seebeck formed a bi-metallic loop, and while heating up one of the junctions with a lamp, he observed the deflection of a compass needle nearby. The design proposed in [1] adopts a similar geometry albeit on a much smaller scale and the lamp is replaced with a laser. This scaling down is important for excitation of plasmonic resonances [1, 14] and results...
in nanoscale confinement of the magnetic field. The optical pulse also allows control over the magnetic pulse duration, while its polarization is critical to generation of the magnetic field. In fact, by modulating the optical polarization it is possible to modulate the polarity of the magnetic field.

In this paper we elaborate on the design proposed in [1], and propose using a nanoring made of four metallic sectors. We numerically investigate the role of the size of these sectors on the generated magnetic field. We analyze the absorbed power and the electron temperature distributions. The latter is used to derive the electromotive force and the resistance which determine the current around the nanoring, and hence drive the magnetic field. We also suggest other routes than tailoring of the metallic sector layout in order to increase the magnetic field.

2. Approach, configuration and methods

The structure proposed in [1] consisted of a ring made of one quadrant of nickel and three quadrants of gold illuminated by a light pulse with linear polarization parallel to one of the metallic junctions. Figure F.1 in [1] shows the azimuthal variation of the absorbed power density along the proposed ring structure. This particular graph provided the insight for the layout of the magnetic sectors proposed in this work in order to maximize the magnetic field generation. Beside the main peak in absorbed power density at 90° (at the Ni–Au junction perpendicular to the light polarization), the presence of two peaks, at 0° (at the Ni–Au junction parallel to the light polarization) and close to −90° can be observed. The peak at 0° suggests that the nickel sector could be made smaller to maximize the temperature difference between the hot and cold junctions, and thereby the electromotive force. As for the peak at −90°, it can be exploited and enhanced by placing an additional nickel sector diametrically opposite to the first one. As a result the nanoring is then composed of four metallic sectors, as shown in figure 1.

The configuration studied here is a bi-metallic nanoring sitting on a silica substrate (see figure 1). This corresponds to a fabricated structure recently reported [15]. We investigate both the 2-sectors and 4-sectors nanorings and the nickel sector angular extent θ is varied (in the 2-sectors design the gold sector extends over 2π−θ while in the 4-sectors design the two gold sectors extend each over π−θ). The nanoring inner diameter, outer diameter, and height, are 70 nm, 190 nm, and 50 nm, respectively. These dimensions result in a plasmonic resonance around 800 nm, a wavelength which matches the most common wavelength of operation of ultrashort pulse lasers, such as titanium–sapphire lasers. The stimulus is a Gaussian optical pulse of central wavelength 800 nm with duration 2Δt = 100 fs (the total 1/e² width is 100 fs), centered at 200 fs with a linear polarization oriented perpendicular to one of the Ni–Au junctions (or two of them in the 4-sectors design). In the following we report the magnetic field at the center of the ring.

We have implemented the 3D model provided in [1] to perform the four steps required for the simulation: (1) calculation of the optical power absorbed in the ring; (2) resolution of the coupled differential equations governing the electron and lattice temperatures; (3) calculation of the thermoelectric current; (4) calculation of the resulting magnetic field. For the first step we used a commercial-grade simulator based on the finite-difference time-domain method [16]. The three subsequent steps were implemented in C++ with an open source finite element library [17]. For every time-increment, calculations 2–4 were performed. The results were
fed into the calculations for the next time-increment. The physical properties input into the model are the same as given in [1].

3. Results

In the following we compare the 2-sector and 4-sector nanoring design in terms of maximum magnetic field generated while we vary the angular extent $\theta$ of the nickel sector(s). The main results of this study are shown in figures 2–5. Figure 2 shows the magnetic pulse generated in response to an optical pulse of fluence $F = 50 \text{ J m}^{-2}$ for the 2-sector and 4-sector nanoring designs with nickel angular extent $\theta = 45^\circ$, $65^\circ$, and $90^\circ$.

![Figure 2](image)

**Figure 2.** Evolution of the magnetic field in response to an optical pulse (see section 2 for details) of fluence $F = 50 \text{ J m}^{-2}$ for the 2-sector and 4-sector nanoring designs with nickel angular extent $\theta = 45^\circ$, $65^\circ$, and $90^\circ$.

Figure 3 shows the magnetic pulse generated in response to an optical pulse of fluence $F = 10$ and $50 \text{ J m}^{-2}$ for the 2-sector and 4-sector nanoring designs with nickel angular extent $\theta = 45^\circ$, $65^\circ$, and $90^\circ$.

![Figure 3](image)

**Figure 3.** Peak magnetic field versus $\theta$, the nickel angular extent, for the 2-sectors and 4-sectors designs in response to optical pulses of fluence $F = 10$ and $50 \text{ J m}^{-2}$. The semi-transparent line and dots are calculated using equations (1)–(3) with a radius of 61 nm, see section 4.

By using a 4-sectors nanoring with nickel sectors of angular extent $\theta = 65^\circ$ the peak magnetic field is 50% higher than in the original design with 2 sectors and $\theta = 90^\circ$. These dependences are further illustrated in figure 3.
where a lower fluence \( (F = 10 \text{ J m}^{-2}) \) is also considered. Although the variations in peak magnetic field are influenced by the fluence, the trends remain the same.

It is instructive to plot the data of figure 3 in terms of ratio, as can be seen in figure 4. For a given fluence, as the extent of the nickel sector is decreased the advantage of the 4-sector over the 2-sector design in terms of maximum magnetic field becomes more and more pronounced. Moreover, the advantage provided by the 4-sectors design is more pronounced at the highest fluence.

It should be born in mind that the lattice temperature increases with increasing fluence and should be kept below the melting point of the nanoring. Gold has the lowest melting point of the two metals used here with \( T_m = 1338 \) K. Figure 5 shows that the maximum lattice temperature in the nanoring remains well below this value. The 4-sectors design shows a significantly lower lattice temperature, giving this design another advantage over the 2-sector design.

4. Analysis and discussion

In this section we aim to further illustrate the differences between the 2- and 4-sector designs. We compare the distribution of the absorbed power and the electron temperature. We calculate averages along azimuthal
positions to estimate the electromotive forces and resistances, from which an estimate of the magnetic field is obtained.

Figure 6 shows maps of the absorbed power density and of the electron temperature for both cases with θ = 65°. Nickel is much more absorbing than gold at 800 nm so that the optical power is mainly absorbed in nickel. The non-uniform distribution of the optical field and the distribution of the metals determine the hot and cold regions in the nanoring. A hot spot forms in the nickel close to the metallic junction perpendicular to the light polarization direction while the other junction is colder. For the 4-sector design the optical power is more uniformly absorbed than in the 2-sector design, see figures 6(a), (b) and 7, and the overall optical absorption is around 13% higher than in the 2-sector design.

The electromotive force depends on the electron temperature gradient, so it is important to analyze the electron temperature distribution in detail. To do so we average the electron temperature across sections of constant azimuthal angle all along the nanoring. The results are plotted in figure 8. Although the shape of the curve correlates with figure 7, which shows the average absorbed optical density, it is ‘smoothened’ by diffusion and coupling to lattice temperature. The shape is also altered by non-linearities, which stem from the fact that material parameters depend on the temperature. As for the absorbed optical power density, the maximum electron temperature reaches a lower value in the 4-sector case compared to the 2-sector one. Because of electron–phonon coupling this should translate into a lower maximum lattice temperature in the 4-sectors case, as indeed observed in figure 5.

Knowing the electron temperatures at the hot and cold junctions, noted $T_H$ and $T_C$, respectively, we can calculate the electromotive force (emf):
\[ \text{emf} = p \int_{T_c}^{T_h} \left( S_{\text{Au}}(T) - S_{\text{Ni}}(T) \right) dT, \]  

where \( S_{\text{Au}} \) and \( S_{\text{Ni}} \) denote the Seebeck coefficients of gold and nickel. In the 2-sector case only one thermocouple is present and the factor \( p \) equals 1, whereas in the 4-sector case two identical thermocouples are present, and \( p \) equals 2.

A summary of the emf generated for each of the cases is presented in figure 9(a). In all cases we observe the presence of an optimum azimuthal extent of the nickel sector(s) at \( \theta = 70^\circ \pm 5^\circ \) where the emf reaches a maximum. For a nanoring with nickel sector(s) extending over 90° the emf is sub-optimal as anticipated in section 2. This can be attributed to the local maximum in electron temperature at the cold junction (see figure 8). This situation is clearly not ideal. On the other hand at the optimal nickel sector extent the electron temperature difference between the hot and cold junctions reaches a maximum. When \( \theta \) is further decreased (see \( \theta = 45^\circ \)) the emf decreases as the cold junction temperature rises again.

While the emf drives the current around the nanoring the resistance impedes its flow, and hence limits the magnetic field. The overall resistance of the ring is obtained by integration:

\[ R = \int \frac{r_c}{\sigma(T)} d\varphi, \]

where \( \varphi \) is the azimuthal angle of the ring, \( r_c \) is a radius (see discussion of equation (3)), \( \sigma \) is the electrical conductivity which is a function of the electron temperature with \( T = T(\varphi) \) (see plots in figure 8), and \( A \) is the vertical cross-sectional area of the ring perpendicular to the azimuthal direction.

The magnetic field at the center of the ring can be calculated from the Biot–Savart law [18]:

\[ B = \frac{\mu_0 I}{2r_c} = \frac{\mu_0 \text{emf}}{2r_c R}. \]

Here we approximate the nanoring to an infinitely thin ring of radius \( r_c \). As a first approximation we used the average radius of the ring, 65 nm, as the radius. However, this underestimated the magnetic field by 12%, and we found that a radius of 61 nm provides a better fit to the fully-numerically calculated magnetic field, see figure 3. This implies that in average the current is circulating nearer the inside radius than the outside one. This can be inferred from figure 6, which shows that the hottest region, which is driving the thermoelectric current, is located towards the inside of the ring.

Knowing that the resistance of nickel is higher than that of gold for the temperature range considered here (see figure E1 in [1]) we expect the overall resistance \( R \) to increase as the nickel sector size is increased from \( \theta = 45^\circ \) to 90°. It can be seen in figure 9(b) that it is indeed the case. More noteworthy is the fact that despite the double amount of nickel, the 4-sector design only exhibits a modestly higher resistance than its 2-sector counterpart (at a high fluence of 50 J m\(^{-2}\) the difference remains less than 8% higher). The reason can be found in the variation of the resistivity of nickel and gold with electron temperature. Like for most materials the resistivity increases with temperature. The doubling of the amount of nickel in the 4-sector nanoring is almost fully compensated by the fact that it operates at a lower temperature than the 2-sector design. As a result the
variation of magnetic field versus $\theta$ nearly mirrors the variation of emf. Another consequence of the temperature dependence of the resistivity is the sub-linear increase of the generated magnetic field with laser fluence. For example while the emf increases about five fold when the fluence is increased from 10 to 50 J m$^{-2}$ the magnetic field increases only 2.5 times. This can be attributed to the increase of resistance from around 7 to 14 $\Omega$, see figure 9(b).

Looking at figure 8 we note that the electron temperature at the hot junction is far below the maximum electron temperature, which is reached further inside the nickel (at 80°, i.e. about 10° from the hot junction). For the case of $\theta = 65^\circ$, which produces the highest magnetic field, we found that tilting the light pulse polarization by 10°, from being perpendicular to the hot junction to making an angle of 80°, we could increase the temperature of the hot junction and increase the maximum magnetic field by about 4% from 0.300 to 0.312 T. For the case of $\theta = 90^\circ$ we checked that having the light polarization perpendicular to the hot junction maximized the magnetic field, as mentioned in [1]. This adjustment of polarization is simple to carry out experimentally but does not bring any significant increase in magnetic field. The hottest spot remains within the nickel and away from the metallic junction. The hot junction is cooled down due to the large thermal conductivity of gold.

A straightforward approach to further increase the peak magnetic field is to use shorter pulses. Using Gaussian pulses, varying the peak power and the pulse duration while keeping the pulse energy constant, we checked that the lattice temperature remains the same. However, a shorter pulse with higher peak power yields a

![Figure 8](image-url)
higher magnetic field. This is a straightforward approach to increasing the magnetic field but going for shorter and shorter pulses means higher cost and greater size of the laser source.

The most radical approach to increasing the generated magnetic field is to change the composition of the nanoring to use more efficient thermoelectric materials. The standard figure of merit (FOM) for thermoelectric devices is given by

$$ZT = \frac{S^2 \sigma}{\kappa} T,$$

where $S$, $\sigma$, $\kappa$, and $T$ are the Seebeck coefficient, electrical conductivity, thermal conductivity and temperature respectively [19]. The thermal conductivity $\kappa = \kappa_{\text{elec}} + \kappa_{\text{latt}}$ consists of electronic and lattice contributions. A material with high Seebeck coefficient, high electrical conductivity and low lattice thermal conductivity will give a high FOM. Among the commercially available thermocouples, type E and type J thermocouples have Seebeck coefficients 2–3 times higher than the gold–nickel couple [20] but the order of magnitude of $ZT$ for the constituent alloys does not exceed $10^{-2}$. This is the same order of magnitude as for nickel. More complex alloys, in particular half-Heusler alloys, can reach a $ZT$ one order of magnitude higher [21]. Semiconductors, and in particular chalcogenides like the bismuth telluride/antimony telluride system have among the highest $ZT$ reported for thermoelectric materials and their fabrication is well established [22–27]. Both their electrical and thermal conductivities are several orders of magnitude lower than that of most metals but their Seebeck coefficient is one or two orders of magnitude higher [23]. Nanostructuring, for example in the form of figure 9.

![Figure 9](image-url)
suggest that several 2D materials show outstanding thermoelectric properties. This includes graphene [28], several metal dichalcogenides such as MoS$_2$ and WS$_2$ [31, 32], and phosphorene [33].

As noted in [19], the dimensionless FOM $ZT$ is derived to compare the efficiency of thermoelectric devices, but the device optimization generally requires more detailed attention to each constituent of $Z$. In addition to the thermoelectric FOM, we also look for other favorable attributes due to the unique features of the nanoring excitation. Unlike conventional thermoelectric devices, there is an ephemeral non-equilibrium state with a large disparity between electron and lattice temperatures. The electron–phonon coupling factor determines the lifetime of this state, and hence governs both the peak field generated and the duration of the pulse. Therefore, materials with low electron–phonon coupling will be strongly suited for this application. The electron and lattice heat capacities are also crucial for the performance of the nanoring. A small electron heat capacity together with a large lattice heat capacity allow for a high electron temperature together with a modest increase in the lattice temperature. Graphene is exceptionally suited in this regard [34].

5. Conclusions

We have shown that the layout of the metallic sectors in a nanoring can be tailored to maximize the magnetic field generated. This was done by changing the sector sizes for nickel and gold in the original design and by introducing a 4-sector design. We showed that this design can provide two significant advantages: a reduced lattice temperature and an increase in the generated magnetic field over the original design. Using averaged values of the electron temperature around the nanoring, we estimated the electromotive force and the resistance in the nanoring, from which we deduced the magnetic field using the Biot–Savart law. Using the average radius of the ring slightly underestimated the magnetic field. We also discussed several routes to generating higher magnetic fields with emphasis on exploiting materials with superior thermoelectric properties.

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