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# Energy and angular momentum transfers from an electromagnetic wave to a copper ring in the UHF band

## *Transferts d'énergie et de moment angulaire d'une onde électromagnétique à un anneau de cuivre dans la bande UHF*

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A B S T R A C T

Electromagnetic waves could carry orbital angular momentum. Such momentum can be transferred to macroscopic objects and can make them rotate under a constant torque. Based on experimental observations, we investigate the origin of orbital angular momentum and energy transfer. Due to angular momentum and energy conservation, we show that angular momentum transfer is due to the change in the sign of angular momentum upon reflection. This leads to a rotational Doppler shift of the electromagnetic wave frequency, ensuring energy conservation.

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R É S U M É

Certaines ondes électromagnétiques peuvent transporter du moment angulaire orbital. Celui-ci peut être transféré à un objet macroscopique et ainsi le mettre en mouvement grâce à un couple constant. À la suite d'observations expérimentales, nous étudions l'origine du transfert de moment cinétique et d'énergie. En considérant les lois de conservation, nous montrons qu'il a pour origine le changement de signe du moment angulaire à la réflexion et entraîne un décalage Doppler rotationnel de la fréquence de l'onde électromagnétique.

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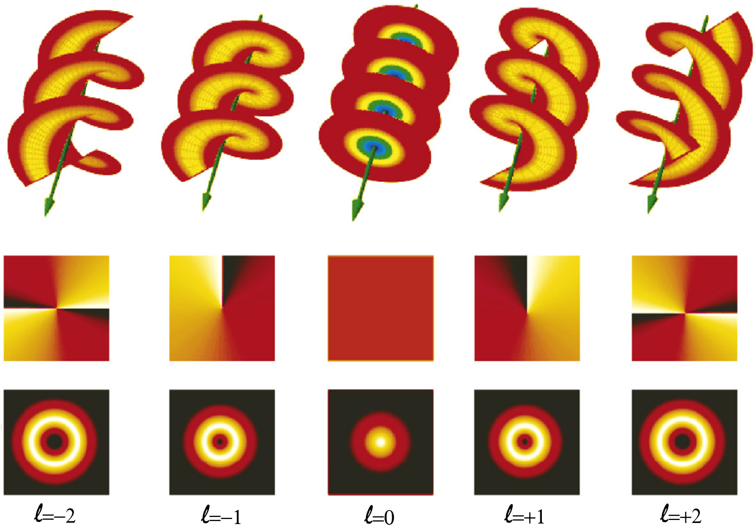


**Fig. 1.** Representation of beams carrying OAM: equiphase surface (top), phase distribution (middle), and intensity distribution (bottom) for $\ell = -2, -1, 0, +1, +2$, in a plane perpendicular to the direction of propagation, showing the vortex structure.

## 1. Introduction

Angular momentum exchanges between Electromagnetic (EM) waves and matter generally lead to mechanical torques. On the one hand, in optics, Beth first demonstrated that the Spin Angular Momentum (SAM) of EM waves can induce rotation of a birefringent plate [1]. This effect has since been confirmed experimentally in the macroscopic domain, both in optics [2,3] and in radio frequencies [4,5]. This transfer has also been evidenced in the microscopic [6] and submicroscopic scales [7,8] using optics only. On the other hand, light can carry Orbital Angular Momentum (OAM) [9–12] that can exceed the maximum SAM of $\hbar$ per photon. This angular momentum has also been used to induce rotation of microparticles [13–15]. In the microwave domain, direct evidence of OAM transfer from an EM wave to a copper ring has been recently reported [16]. Yet, since copper is considered like a perfectly conducting material in microwaves, the EM waves cannot be absorbed. OAM can only be transfered via reflection. However, it has been demonstrated [17] that an EM wave carrying OAM cannot transfer angular momentum to a perfectly conducting plate by reflection. Then the question of the origin of the transfer mechanism arose. Besides, in the interaction of OAM carrying waves with rotating objects, energy can be transferred from the object to the wave via frequency change because of the rotational Doppler effect. It has been observed both in radio [18] and in optics [19]. However, in the exchange of SAM or OAM to objects, energy considerations have hardly ever been considered, either in optics or in radio. The aim of this article is thus to explore the origin of the exchange between EM microwaves carrying OAM and a large suspended ring and to investigate energy conservation in such a system. The article is organized as follow. First we recall some basic properties concerning OAM in section 2. We then shortly present the experimental set up, theoretical considerations, and the main results in sections 3, 4 and 5, respectively. We then discuss the transfer mechanism and compare it to other mechanisms in section 6, before addressing the problem of energy conservation in section 7, and reaching a conclusion.

## 2. Basic properties of OAM waves

Although angular momentum was already described in Poynting's early work [20,21], it has gained a tremendous renew of interest in the 1990s [9,22] and is now an exponentially growing field. Usually an EM field carrying OAM is described as a beam that has a hole in the center of its amplitude distribution, and a phase $\varphi$ that is not uniform (see Fig. 1). Its phase varies as $\varphi = \ell\theta$, $\theta$ being the polar coordinate and $\ell$ being the so-called topological charge. On a plane perpendicular to the direction of propagation, it has a $2\pi\ell$ variation around the axis of the beam. This beam is also sometimes called a vortex beam.

In optics, it is usually generated from the fundamental mode of a laser beam using either transformation optics with dove prisms [9], spiral phase plates [23], using holograms [22] or spatial light modulators [24].

In radio, the renew of interest originates from an article published in 2007 [25]. OAM beams can be generated in the same way as in optics, using spiral phase plates [26], or holograms [27]. However, since the wavelength is much higher than in optics, there exist specific experiments based on dipole arrays [25,28,29], discrete step phase masks [30], twisted reflectors [31], dedicated designed circular antenna [32] or specific lenses [33]. The detection can be performed, both in optics and radio, using the transformation optics in reverse or using interferences with plane waves [34] or self interferences using triangular apertures [35] or Young double-slit experiments [36]. For review articles, the reader can refer, for example, to [10–12,37].

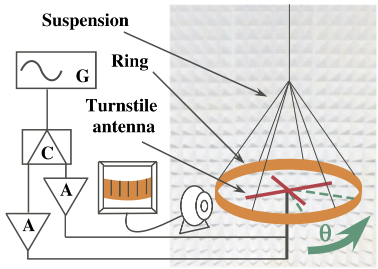


**Fig. 2.** Experimental set-up. G: radio frequency generator, C: −3-dB coupler, A: 40-dB gain amplifier. The experiment is performed in an anechoic chamber.

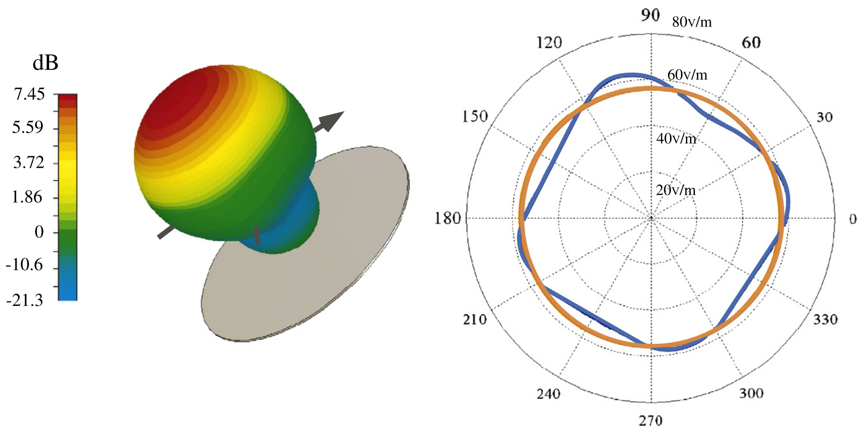


**Fig. 3.** Three-dimensional radiation pattern simulated with CST software (left). The axes (black lines) are in the plane of the antenna. The disk corresponds to a ground plane. Right: radiation pattern in the plane of the antenna. Blue curve: simulated radiation pattern. Red curve: ideal isotropic radiation pattern.

Concerning the applications, some authors take advantage of the vortex structure to guide atoms or particles like in a funnel [38]. Nevertheless, the main suggested application remains in telecommunications in radio or in optics. It has been recently demonstrated that the bit rate of free-space communications can be dramatically enhanced without requiring more bandwidth, just by exploiting the spatial phases of twisted beams and the orthogonal properties of the OAM modes. This has been evidenced with EM waves, both in radio [31,39] and in optics [40–42]. However, especially in radio for long-distance communications, the mode attenuation that strongly increases with the twisted degree of the OAM wave [43] leads to a low link budget that may be detrimental to potential applications.

Besides, the authors only exploit the orthogonality of the different OAM modes. In principle, this could be also performed using other spatial phases distribution for example using Hermite Gaussian modes instead of Laguerre Gaussian modes. The application is not specific to the OAM character of the twisted beams. In the following of the paper, we will concentrate on the mechanical properties of twisted beams only and on the transfer of OAM to a macroscopic object in the radio frequency band, in the Ultra High Frequency (UHF) band.

## 3. Experimental set-up

The experimental set-up has been described elsewhere [16]. For the sake of clarity, we will only recall the main characteristics (see Fig. 2). The EM field carrying OAM is generated by a so-called turnstile antenna comprised of two 17-cm-long, 2-mm-diameter copper dipole antennas. We perform the experiment at a frequency $\nu = 870$ MHz. A −3-dB coupler splits the signal generated from a sinusoidal frequency synthesizer into two parts, and induces a $\phi_1 - \phi_2 = \pm\pi/2$ phase between the outputs. The two signals are amplified by two 40-dB gain amplifiers and then sent to the antennas. The maximum total output for each dipole is 25 W. The rotating object is a 5-cm-high copper ring. The suspension of the torsion pendulum is a 2-m-long cotton thread, 0.5 mm in diameter, fixed to the ceiling. To avoid any spurious EM effect, the experiment is confined in an anechoic chamber dedicated to this frequency range. Special care is taken to isolate the set-up from any mechanical vibration. An angular graduation is glued on the copper ring, and rotation is recorded on a computer via a webcam.

This turnstile antenna is usually used to radiate a circularly polarized field in a direction perpendicular to the plane of the antenna. However, it also radiates an electric field carrying OAM in the plane of the antenna. We are here interested in this latter case. Nevertheless, whereas in most of the applications, the EM beam can be approximated by a Gaussian beam within the framework of the paraxial approximation, the radiated EM field is here a 2-D spherical (see Fig. 3) wave radiated in the plane of the antenna. This is quite a different scheme than the one used for usual OAM EM fields.

## 4. Theoretical considerations

The theoretical expressions of the EM field and of the SAM and OAM have been detailed in [16]. We will only recall here the main results.

The complex magnetic field in the plane of the turnstile antenna, writes at a point $M$

$$\mathbf{B}(M,t) = -\frac{\mu_0}{4\pi}\frac{\mathrm{j}\omega}{r^2}p_0(1-\mathrm{j}kr)\mathrm{e}^{\mathrm{j}(kr-\omega t)}\mathrm{e}^{\mathrm{j}(\theta-\pi/2)}\mathbf{e_z} \tag{1}$$

where $r = OM$, $\omega$ is the pulsation of the current, $p_0$ is the dipole moment, $\mu_0$ is the magnetic permeability, and $k$ is the wave vector modulus.

The complex electric field writes

$$\mathbf{E}(M,t) = \frac{\mathrm{e}^{\mathrm{j}\theta}}{4\pi\epsilon_0}\frac{p_0}{r^3}\mathrm{e}^{\mathrm{j}(kr-\omega t)}\left[2\,(1-\mathrm{j}kr)\mathbf{e}_{\boldsymbol{\rho}} - \mathrm{j}(1-\mathrm{j}kr-k^2r^2)\mathbf{e}_{\boldsymbol{\theta}}\right] \tag{2}$$

$\epsilon_0$ being the electric permittivity.

One can note first that, in the plane of the antenna, for a given distance $r$ from the turnstile antenna, the modulus of the electric field is constant, its direction rotates around $z$, and its phase varies as a function of $\theta$, from 0 to $2\pi$ in one turn. It must be a wave carrying OAM with a topological charge $\ell = 1$. Second, the Poynting vector, which is the vectorial product of the **E** and **B** fields, has a component along $\mathbf{e}_{\boldsymbol{\rho}}$, which is the propagation direction, and a component along $\mathbf{e}_{\boldsymbol{\theta}}$. This last term results from the **E** component along $\mathbf{e}_{\boldsymbol{\rho}}$. It is usually assumed to be a near-field component and considered as negligible. However, since Angular Momentum (AM) is the vectorial product of the position (along $\mathbf{e}_{\boldsymbol{\rho}}$) and the Poynting vector, only the component of the Poynting vector along $\mathbf{e}_{\boldsymbol{\theta}}$ has to be taken into account. Then, the near-field component of the electric field alone contributes to the AM.

One can thus evaluate the total AM $J$ on the ring

$$\mathbf{J} = \frac{2\,\mu_0\,\omega}{(4\pi)^2}\frac{p_0^2}{r^2}\pi\,\Omega\,(k^2r^2+1)\,\mathbf{e_z} \tag{3}$$

where $\Omega$ is the solid angle subtended at the center of the antenna by the ring. The SAM $S$, which is the vectorial product of the position times the electrical susceptibility by the vectorial product of the electric field and the vector potential, writes

$$\mathbf{S} = \frac{2\,\mu_0\,\omega}{(4\pi)^2}\frac{p_0^2}{r^2}\pi\,\Omega\,\mathbf{e_z} \tag{4}$$

and by subtraction of Eq. (3) and Eq. (4), the OAM $L$ equals

$$\mathbf{L} = \mathbf{J} - \mathbf{S} = \frac{2\,\mu_0\,\omega}{(4\pi)^2}p_0^2\,\pi\,\Omega\,k^2\,\mathbf{e_z} \tag{5}$$

It has to be noted that, according to Eq. (5), the OAM has the same expression in the near field and the far field. Besides, as already mentioned, it is the component of the electric field along the radial direction, which is usually considered as a near-field component that contributes to the OAM. This remark will be important in section 6.

## 5. Experimental results

The experimental results are shown in Fig. 4. We have evidenced a uniformly accelerated rotation of the pendulum. In Fig. 4a, we have plotted the rotation versus time for three different radiated powers. The rotation speed depends on power, as expected. As the phase between the two dipole antennas is reversed (from $+\pi/2$ to $-\pi/2$), the sign of the OAM, which switches from $\ell = +1$ to $\ell = -1$, changes. The sign of the torque changes as well. We experimentally find a change in the direction of rotation of the pendulum. Besides, the rotation curves for $\ell = +1$ and $\ell = -1$ are nearly perfectly symmetric. Of course, when the two dipole antennas are fed in phase by the same signal, no rotation is observed.

Fig. 4b shows the angular acceleration induced by the EM field versus the power transmitted to each dipole. The acceleration has a linear dependence on power, as expected, that holds over one order of magnitude. Note also that the linear coefficient is exactly reverse for the other direction of rotation. From Fig. 4b, for a 25-W power, we find an acceleration of $7.8 \cdot 10^{-4\circ}/\mathrm{s}^2$, which corresponds to an OAM torque of $\Gamma_{\mathrm{ex}} = 1.1 \cdot 10^{-8}$ N · m. This is in reasonable agreement with the expected value of the torque [16].

## 6. Transfer mechanism

Let us now focus on the OAM transfer mechanism and on the rotation of the ring. The next two sections deal with the state of art about SAM and OAM transfers, whereas section 6.3 considers the specific case presented in this article between OAM and a copper ring. There are many ways to rotate objets using EM radiation. This can be performed either with linear momentum or with AM. The former takes advantage of specially shaped three-dimensional objects and the scattering of

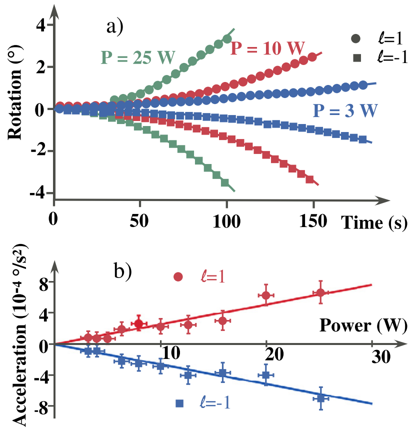


**Fig. 4.** a) Rotation versus time for a $\pi/2$ (circle) and $-\pi/2$ (square) phase between the two dipole antennas for three different transmitted powers. b) Acceleration versus transmitted power for a $\pi/2$ (circle) and $-\pi/2$ (square) phase between the two dipole antennas.

ordinary light (see, for example, [44]). The radiation pressure or/and the scattered light exerts a force that leads to a torque on such objects. One can also transfer AM via thermocapillary propulsion observed for asymmetric objects [45] based on heat transfer due to light absorption. One can mention the diffraction of a plane wave on an asymmetric object, [46,47], where the diffracted light carries OAM. As for the latter scheme, one has to distinguish between SAM and OAM.

### *6.1. SAM transfer*

For SAM, the rotating objects could be birefringent or absorbing objects. In the case of absorbing objects, the torque is applied by the absorbed light and the AM conservation implies that each absorbed photon transfers $\hbar$. In the case of birefringent objects, diffraction is responsible for the torque. In the ideal case of $\lambda/2$ phase plates, each circularly polarized photon flips its polarization, leading to a $2\hbar$ per photon transfer. It could even be increased to $4\hbar$ by adding a $\lambda/4$ phase plate and a mirror [1,3,48]. Birefringent particles could also follow adiabatically a rotating polarization [6]. The speed of rotation is then imposed by the rotation frequency of the polarization.

### *6.2. OAM transfer*

For OAM, the transfer mechanism is most of the time from absorption and each photon transfers $\ell\hbar$, $\ell$ being the topological charge of the beam. For purely transparent particles, the helical phase of the incident beam is not changed while crossing the objects. Hence, the objects cannot interact with OAM [37]. However, when these objects introduce astigmatism, the phase front is modified and OAM could be transferred. Yet, since the wave front is modified, it could not be considered as purely transparent objects any more. For example, a “free” cylindrical lens could rotate under the influence of an OAM field [49]. As for birefringent objects, microparticles can also be trapped in patterns that are rotating. These particles would then follow adiabatically the pattern rotation at a low frequency of the order of few Hertz [50]. However, such mechanical rotation is not directly linked to the OAM of light.

There is one distinction between SAM and OAM that has to be noted. SAM is a local concept. The direction of the EM field rotates at every position. Hence, whatever the size of the particle, it rotates around its own axis. On the other hand, OAM is a global concept. The Poynting vector is spiraling around the direction of propagation of the field. Thus, the vortex axis and the center of the particle have to be aligned, and the size of the particle has to be of the order of the size of the beam [13] in order to make the particle rotate around its own axis; otherwise, the particles are just rotating around the EM vortex [51,52].

### *6.3. OAM transfer to a copper ring in the UHF band*

In our case, the OAM transfer mechanism is not by absorption, since in the UHF band copper is nearly a perfect reflector. There is also hardly any EM radiated outside the ring in the plane of the antenna, as can be seen in Fig. 5, which is a simulation of the EM field including the ring and the antenna. The ring reflects nearly all the EM fields radiated in the plane of the antenna. Most of the energy is radiated perpendicular to the antenna. Thus the transfer mechanism can only be via reflection. However, it has been demonstrated that, for a perfectly conducting plane, there could not be any EM AM transfer [17].

The argument is the following. To ensure the continuity of the EM fields, the transverse electric fields have to reverse sign upon reflection. At normal incidence, since the field is a transverse quantity, the electric field has to reverse its sign.

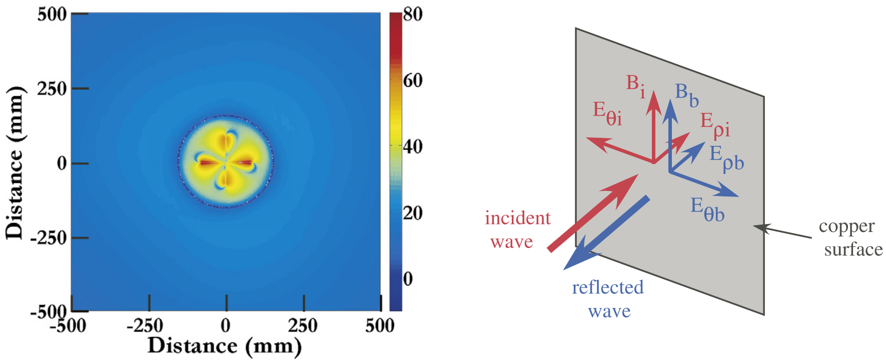


**Fig. 5.** Left: CST software simulation of the electric field distribution, including the ring and the antenna in the middle. The scale corresponds to the amplitude of the electric field in volt per meter. Right: Illustration of the reflection of the EM field exemplifying the continuity of the E field. The AM is reverse upon reflection. $i$ index stands for incident (red) $b$ index stands for reflected (blue).

Thus the Poynting vector changes its sign since it propagates backward. Upon reflection on a plane, the vectorial product changes its sign, thus the AM does not change its sign [17].

However, in [17], only the transverse components of the EM fields have been taken into account. In our particular case, as already mentioned in section 4, the longitudinal component of the electric field only contributes to the OAM, which does not change sign upon reflection. There is no contradiction with reference [17]. Whereas the transverse components of the fields annihilate on the copper surface, the longitudinal components does not. There is a small electric field close to the ring (see Fig. 5). Then, as can be seen on the right part of Fig. 5, upon reflection, the magnetic field does not change its sign as well as the longitudinal component of the electric field. The AM consequently changes its sign. Then, upon reflection, a $2\hbar$ is transferred to the ring by each reflected photon. This transfer mechanism is very different from the other mechanisms of AM transfer.

## 7. Energy conservation

Since the ring is set into rotation, it must acquire energy. One may then wonder where this energy comes from. Copper is a nearly perfect conductor. The electromagnetic radiation is thus mainly reflected and hardly absorbed. To insure energy conservation, the frequency of the EM field has to be lowered. The only way for doing it is via Doppler effect. Nevertheless, the incoming EM field is perpendicular to the velocity. One has to invoke the rotational Doppler shift [18,19] instead of the usual Doppler shift. The energy shift for the rotations we observe is of the order of a fraction of hertz since the rotation of the ring is slow. It is hardly noticeable. The increase in the energy of the ring due to rotation is compensated by a lowering of photon energy that enables energy conservation.

We have also been able to slow down the rotation of the ring by applying an electromagnetic radiation with the appropriate handedness, i.e. with the correct topological charge. Curiously, in that case, the ring is loosing energy, which must have been transferred to the EM field. Then the frequency of the EM field must have increased. It was also too low to be detectable.

## 8. Conclusion

In conclusion, we have reported the transfer of OAM from an EM field to a macroscopic copper ring. We have emphasized that the transfer mechanism is due to the reflection of the EM field on the ring. This AM transfer is linked to an energy transfer from the EM field to the rotation of the ring. The EM field frequency is shifted to a lower frequency. It would be now stimulating to try to detect a microwave field carrying more than one $\hbar$ per photon. Then energy transfer could be much more efficient since it is proportional to the topological charge of the beam. Finally, this transfer mechanism resembles the transfer of AM in the case of the induction motor for magnetic field. It could shine new perspectives for this kind of motor.

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