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Olivier Emile, Christian Brousseau, Janine Emile

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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

Olivier EMILE

Université Rennes 1, 35042 Rennes cedex, France

Christian BROUSSEAU

UMR CNRS 6164 IETR, Université Rennes 1, 35042 Rennes cedex, France

Janine EMILE

UMR CNRS 6251 IPR, Université Rennes 1, 35042 Rennes cedex, France

Kouroch MAHDJOUBI

UMR CNRS 6164 IETR, Université Rennes 1, 35042 Rennes cedex, France

Abstract

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

Résumé Certaines ondes électro-magnétiques peuvent transporter du moment angulaire orbital. Celui-ci peut être transféré à un objet macroscopique et

*Corresponding author

Email address: olivier.emile@univ-rennes1.fr (Olivier EMILE)

ainsi le mettre en mouvement grâce à un couple constant. Suite à des 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.

Keywords: Orbital angular momentum, Twisted waves, Angular momentum and energy transfer, Ring rotation.

Mots clés : Moment angulaire orbital, Ondes spirales, Transfert de moment angulaire et d'énergie, Rotation d'un anneau.

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1. Introduction

Angular momentum exchanges between Electromagnetic (EM) waves and matter generally lead to mechanical torques. On the one hand in optics, Beth first demonstrates 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 radiofrequencies [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, 10, 11, 12] that can exceed the maximum SAM of \hbar per photon. This angular momentum has also been used to induce rotation of microparticles [13, 14, 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 cannot be absorbed. It can only be transfer via reflection. However, it has been demonstrated [17] that an EM 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 the 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 the 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 gain a tremendous renew of interest in the 90's [9, 22] and is now an exponentially growing field. Usually an EM field carrying OAM is described
35 as a beam that has a hole in the center of its amplitude distribution, and a phase φ that is not uniform (see Fig. 1). Its phase varies as $\varphi = \ell\theta$, θ being the polar coordinate and ℓ 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.

40 In optics, it is usually generated from the fundamental mode of a laser beam using either transformation optics with dove prisms [9], a spiral phase plate [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
45 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
50 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, 11, 12, 37].

Concerning the applications, some authors take advantages of the vortex structure to guide atoms or particles like in a funnel [38]. Nevertheless, the
55 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
60 [31, 39] and in optics [40, 41, 42]. However, especially in radio for long distance

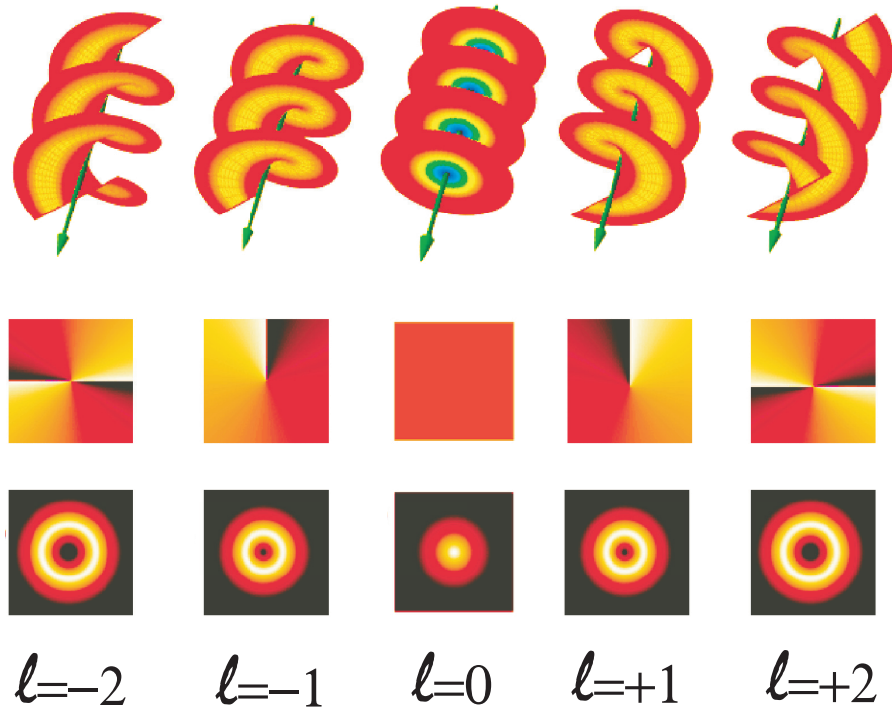


Figure 1: Representation of beams carrying OAM: equiphase surface (top), phase distribution (middle), and intensity distribution (bottom) for $\ell = -2, -1, 0, +1, +2$, in a plane perpendicular to the direction of propagation showing the vortex structure.

Faisceaux transportant du moment angulaire orbital : surface équiphase (haut), distribution de phase (milieu) et distribution d'intensité (bas) pour $\ell = -2, -1, 0, +1, +2$, dans un plan perpendiculaire à la direction de propagation, montrant la structure en vortex.

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 composed of two 17-cm-long, 2-mm-diameter copper dipole antennas. We perform the experiment at a frequency $\nu = 870$ MHz. A -3dB coupler splits the signal generated from a sinusoidal frequency synthesizer in 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-height-copper ring. The suspension of the torsion pendulum is a 2 m-long, 0.5 mm-diameter cotton thread, 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 the 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

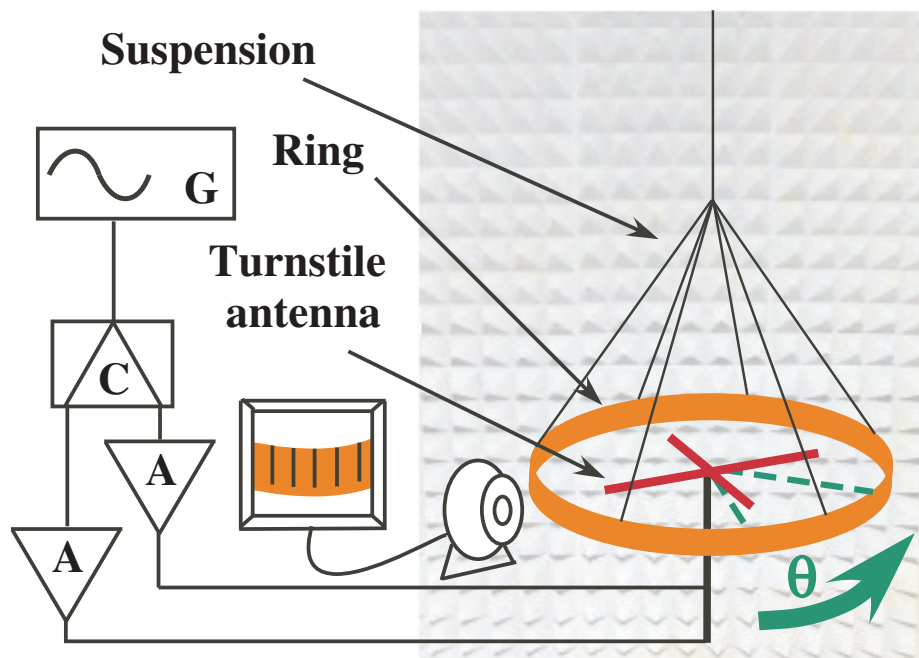


Figure 2: Experimental set-up. G: radio frequency generator, C: -3 dB coupler, A: 40 dB gain amplifier. The experiment is performed in an anechoic chamber.

Dispositif expérimental. G : générateur radio fréquence, C : coupleur -3dB, A : amplificateur de gain 40 dB. L'expérience est réalisée dans une chambre anéchoïque.

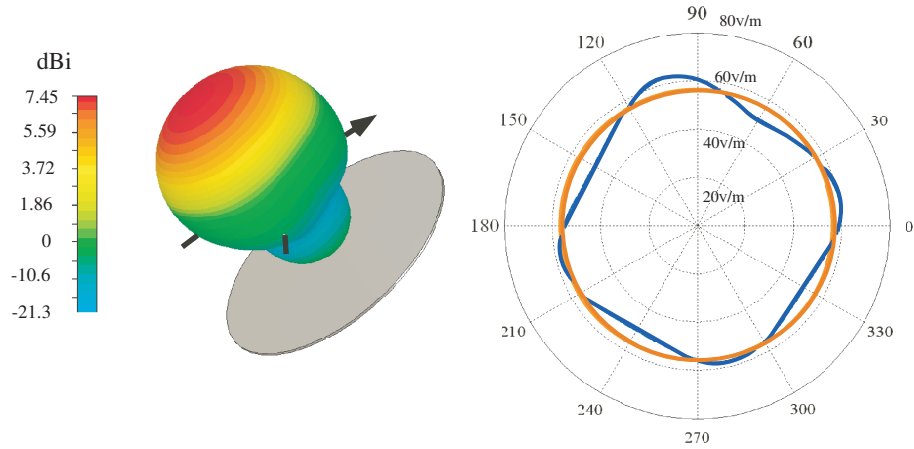


Figure 3: Three dimensional radiation pattern simulated with CST software (left). The axis (black lines) are in the plane of the antenna. The disk corresponds to a ground plane. Right: radiation pattern in the plane of the antenna. Blue curve: Simulated radiation pattern. Red curve: Ideal isotropic radiation pattern.

Diagramme de rayonnement en trois dimensions simulé avec le logiciel CST (gauche). Les axes (droites noires) sont dans le plan des antennes. Le disque correspond à un plan de masse. Droite: Diagramme de rayonnement en deux dimensions dans le plan des antennes. Courbe bleu : simulations. Courbe rouge : diagramme isotrope idéal.

90 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
 95 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

100 a point M

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

where $r = OM$, ω is the pulsation of the current, p_0 is the dipole moment, μ_0 is the magnetic permeability and k is the wave vector modulus.

The complex electric field writes

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

ϵ_0 being the electric permittivity.

105 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 θ , from 0 to 2π 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 \mathbf{E} and \mathbf{B} fields
 110 has a component along \mathbf{e}_ρ which is the propagation direction and a component along \mathbf{e}_θ . This last term results from the \mathbf{E} component along \mathbf{e}_ρ . It is usually assumed to be a near field component and considered as negligible. However, since the Angular Momentum (AM) is the vectorial product of the position (along \mathbf{e}_ρ) and the Poynting vector, only the component of the Poynting vector
 115 along \mathbf{e}_θ 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

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

where Ω 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
 120 potential, writes

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

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

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

It has to be noted that, according to equation 5, the OAM has the same expression in the near field and the far field. Besides, as already mentioned, it is
125 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 paragraph 6.

5. Experimental results

The experimental results are shown on Fig. 4. We have evidenced a uni-
130 formly accelerated rotation of the pendulum. In figure 4a we have plotted the rotation versus time for three different radiated powers. The rotation speed depends on the power, as expected. As the phase between the two dipole antennas is reversed (from $+\pi/2$ to $-\pi/2$), the sign of the OAM, that switches from $\ell = +1$ to $\ell = -1$. The sign of the torque changes as well. We experimentally
135 find a change of 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.

Figure 4b shows the angular acceleration induced by the EM field versus
140 the power transmitted to each dipole. The acceleration has a linear dependence on the 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 $7.8 \cdot 10^{-4} \text{ }^\circ/\text{s}^2$ which corresponds to an OAM torque of $\Gamma_{ex} = 1.1 \cdot 10^{-8} \text{ Nm}$. This is in reasonable
145 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 paragraphs deal with the state of art about SAM and OAM transfers, whereas paragraph 6.3 considers the specific case presented in this
150 article between OAM and a copper ring. There are many ways to rotate objects

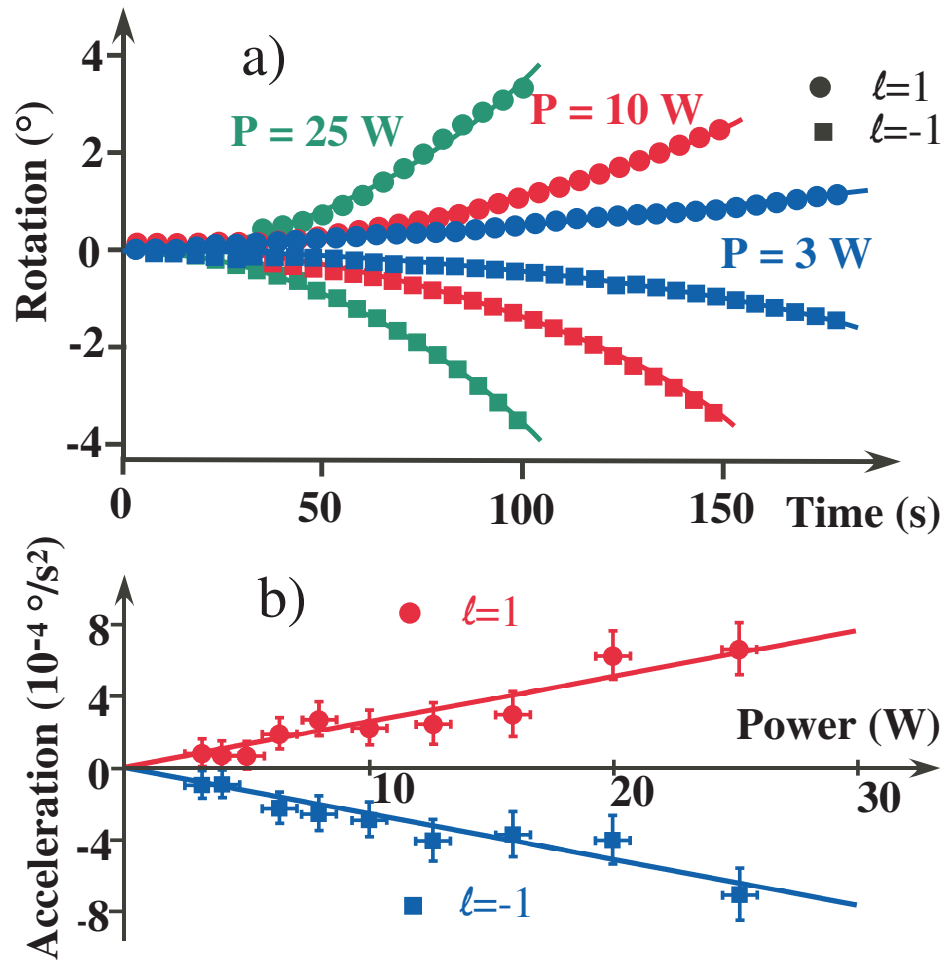


Figure 4: a) Rotation versus time for a $\pi/2$ (circle) and $-\pi/2$ (square) phase between the two dipole antennas for three different transmitted powers. b) Acceleration versus transmitted power for a $\pi/2$ (circle) and $-\pi/2$ (square) phase between the two dipole antennas.

a) Angle de rotation en fonction du temps pour un déphasage de $\pi/2$ (rond) et $-\pi/2$ (carré) entre les deux dipôles formant l'antenne tourniquet pour trois puissances différentes. b) Accélérations correspondantes, en fonction de la puissance.

using EM radiation. It can be performed either with the linear momentum or with the AM. The former takes advantages of specially shaped three-dimensional objects and the scattering of 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
155 asymmetric objects [45] based on heat transfer due to the 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.

160 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
165 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.

170 6.2. OAM transfer

For OAM, the transfer mechanism is most of the time from absorption and each photon transfers \hbar . 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
175 astigmatism, the phase front is modified and OAM could be transferred. Yet, since the wave front is modified, it couldn't 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

180 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,
185 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 rotating around its own
190 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.
195 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 couldn't be any EM AM transfer [17].

200 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. Thus the Poynting vector changes its sign since it propagates backward.
Upon reflexion on a plane, the vectorial product changes its sign, thus the AM
205 doesn't 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
doesn't change sign upon reflection. There is no contradiction with reference

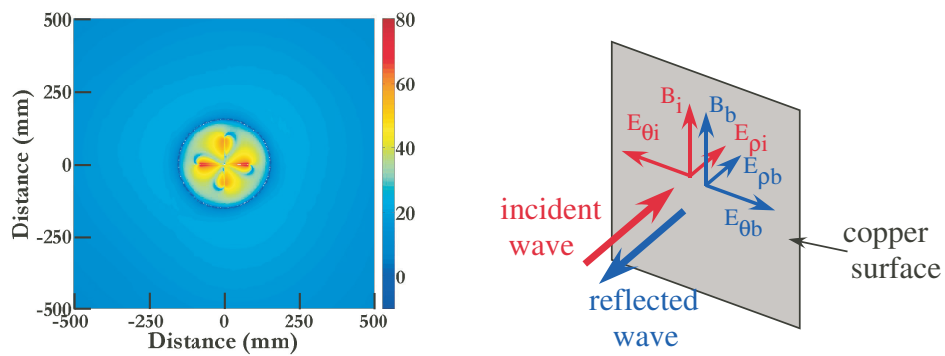


Figure 5: Left: CST software simulation of the electric field distribution, including the ring and the antenna in the middle. The scale corresponds to the amplitude of the electric field in volt per meter. Right: Illustration of the reflection of the EM field exemplifying the continuity of the E field.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

Gauche : simulation à l'aide du logiciel CST de la distribution du champ électrique dans le plan de l'antenne, en incluant l'anneau et l'antenne au centre. L'échelle correspond à l'amplitude du champ électrique en volt/mètre. Droite : illustration de la réflexion d'un champ EM soulignant la continuité du champ électrique. Le moment angulaire orbital change de signe à la réflexion. Indice i pour incident et b pour réfléchi.

210 [17]. Whereas the transverse components of the fields annihilate on the copper
surface, the longitudinal components doesn't. There is a small electric field close
to the ring (see figure 5). Then, as can be seen on the right part of figure 5, upon
reflection, the magnetic field doesn't change its sign as well as the longitudinal
component of the electric field. The AM consequently changes its sign. Then
215 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.
220 EM is 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
225 hertz since the rotation of the ring is slow. It is hardly noticeable. The increase
of the energy of the ring due to rotation is compensated by a lowering of the
photon energy that enables energy conservation.

We have also been able to slow down the rotation of the ring by applying
the EM with the correct handedness. Curiously, in that case, the ring is loosing
230 energy that must have been transfer to the EM field. Then the frequency of the
EM field must have increased. It was also too low to be detectible.

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
235 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 microwave field carrying more than one \hbar per photon. Then the 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 in this kind of motor.

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