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## PAPER

## Optical orbital angular momentum transfer to electronic currents

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E-mail: [olivier.emile@univ-rennes.fr](mailto:olivier.emile@univ-rennes.fr)**Keywords:** orbital angular momentum of light, torque, angular momentum transfer

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## Abstract

Light orbital angular momentum (OAM) is transformed into an electronic current loop in a copper coil, by absorption of the optical radiation. The measurement of this current, that is in the  $10^{-17}$  A range, makes it possible to evaluate and quantify the OAM carried by an electromagnetic wave in the optical domain. In particular, it determines unambiguously the torque generated by the beam and its topological charge. The induced current depends on the optical power and on the wavelength, in good agreement with theoretical predictions. Further possible developments towards an optical torque-meter are then discussed.

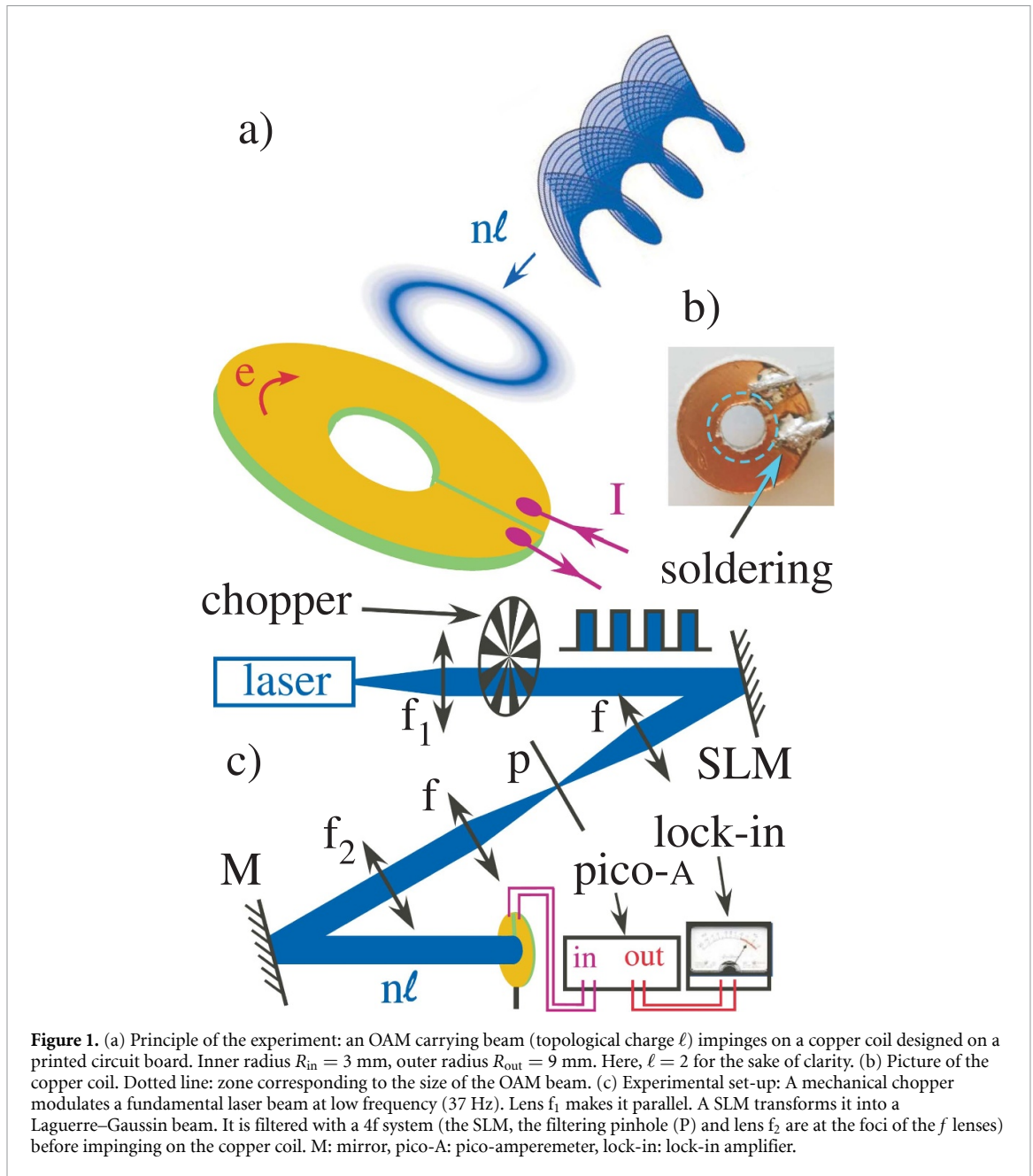
## 1. Introduction

The only experiment that Einstein carried out has shown the link between the mechanical angular momentum and the magnetic momentum [1, 2]. This magnetic momentum was later recognized as being related to the spin of the electron [3]. Thus, an electronic spin can generate a torque. This is not limited to electrons and it is true for all spins, even for massless particles like photons. Beth, in his famous experiment, managed to rotate a birefringent plate with circularly polarized light using parametric amplification [4]. This has since inspired several experiments [5], with a direct evidence of the torque on macroscopic [6] and microscopic objects [7]. Still in electromagnetism, the rotation of objects was also observed using orbital angular momentum (OAM) at the atomic [8], microscopic [9, 10] and macroscopic scales [11, 12]. OAM and spin angular momentum (SAM) are usually considered as uncorrelated variables within the paraxial approximation [13], which was the case there. It has even been evidenced in acoustics [14, 15]. Whereas in the Einstein-de Haas experiment, an electric current in a coil (solenoid) induces an orientation of the electronic spins, one may wonder whether the OAM of light could induce a current in a coil and could thus make it possible to measure quantitatively the torque carried by the light.

Actually, the angular momentum is mostly investigated indirectly, either by using a quarter wave plate and a polarizer [16], for SAM, or by interferometric techniques that measure the phase [17–19], or phase plates to bring back beams to fundamental beams [20], in order to deduce then the topological charge, for OAM. It is also possible to use the response to OAM of atoms or ions to determine the topological charge. In particular, in some cases, the OAM matter interaction modifies the selection rules [21], is sensitive to the orientation of the applied magnetic field [22], or changes the profile of the transmitted light [23]. However, such techniques require the knowledge of the light power and/or the wavelength to evaluate the torque. The purpose of this work is to propose a method for a direct measurement of the torque carried by a light beam.

## 2. Experimental set-up

To this end, we have specially designed a copper coil, that is not fully closed, on a printed circuit board (see figure 1(a)). Copper is reddish and absorbs partly green and blue light [24]. The energy and also the angular momentum can thus be transferred to the quantum electron gas of the metal. We tin-welded two copper wires at the two ends of the coil. They are connected to a pico-ampere-meter (picoammeter Keithley 6485) in order to close the circuit. The light beam originates from a laser with several possible wavelengths (OXXIUS



LBX-4 C, wavelengths  $\lambda_1 = 404$  nm,  $\lambda_2 = 488$  nm,  $\lambda_3 = 532$  nm, and  $\lambda_4 = 561$  nm, maximum available power 200 mW, linear polarization).

A Spatial Light Modulator (SLM, Holoeye PLUTO-2-NIR-011) transforms the fundamental laser beam into a Laguerre–Gaussian beam [25, 26] with a topological charge that can be set up to  $\ell = \pm 50$ . The light is filtered with a 4-f system (see figure 1(c)) and a pinhole. Since Laguerre–Gaussian beams have a hole in the center of the intensity distribution, we managed, using a converging lens  $f_2$ , so that the whole beam impinges on the copper coil. Besides, we carefully checked that the beam is well centered on the coil. Actually, by changing the position of lens  $f_2$ , we make sure that, for every  $\ell$  value, the maximum intensity of the ring shaped OAM beams corresponds to the same radius of approximately 3.5 mm. This radius has been chosen in order to avoid the soldering points (see figure 1(b)). We could have used perfect optical vortices [27] instead, since the size of these beams weakly varies with  $\ell$ . However, we would have restricted our study to a specific class of OAM beams. Because the current might be very weak, we modulate the laser beam with a chopper at a low frequency (37 Hz) and use a lock-in amplifier at the output of the analog signal from the pico-ampere-meter to measure the intensity signal.

### 3. Torque and current estimation

For a linearly polarized beam carrying a topological charge equal to  $\ell$ , each photon has an OAM equal to  $\hbar\ell$  ( $\hbar = h/(2\pi)$ ,  $h$  being the Planck constant). Of course, for a circularly polarized beam, the angular momentum per photon should be changed to  $\hbar(\ell + \sigma)$ , with  $\sigma = +1$  for a right circularly polarized beam and  $\sigma = -1$  for a left circularly polarized beam. For a beam with a flux of  $n$  photons per second, the available torque  $\Gamma$  is

$$\Gamma = n\hbar\ell. \quad (1)$$

For a given optical power  $P$  and a given wavelength  $\lambda$ , ( $\lambda = c/\nu$ ,  $c$  being the light velocity and  $\nu$  its frequency), the number of photons is linked to the optical power ( $n = P/(h\nu)$ ). Thus, the torque could be expressed as

$$\Gamma = \frac{P}{2\pi c} \lambda \ell. \quad (2)$$

This optical torque acts on the electrons of the copper coil and makes them rotate. The Poynting vector indeed spirals along the direction of propagation of the field [28]. Thus, the electrons have trajectories that follow the projection of the Poynting vector on the coil. They rotate following the light intensity distribution and then the shape of the coil.

More precisely, the angular momentum theorem [29] states that the derivative of the angular momentum of electrons is equal to the torque. However, such electrons encountered several collisions. Thus, the drift angular momentum  $j$  of the electrons is then

$$j = \tau\Gamma \quad (3)$$

where  $\tau$  is the mean free time between collisions. It can be evaluated using the resistivity of copper  $\rho$ , the electron mass  $m$ , its charge  $e$  and  $N$  the density of free electrons in copper ( $N = 8.4 \times 10^{28} \text{ e m}^{-3}$ ) [30]

$$\tau = \frac{m}{\rho N e^2} = 24.6 \times 10^{-15} \text{ s} \quad (4)$$

in agreement with the estimated value of  $\tau = 36 \text{ fs}$  [31].

On the other hand, the angular momentum of electrons could be linked to a current  $I$  within the coil

$$j = IS \frac{2m}{e} \quad (5)$$

$S$  being the surface of the loop of the electron in the coil [3]. Then, one finally gets

$$I = \ell \frac{P}{2\pi c} \frac{\lambda}{S} \frac{e}{2m} \eta(\lambda) \tau \quad (6)$$

$\eta(\lambda)$  being the absorption of copper that of course depends on  $\lambda$ .

The torque, for a monochromatic light, is thus proportional to the current in the coil. This value of the current corresponds to a measurement of the torque. Both the current and the torque vary linearly with the power. At a given optical power, they vary linearly with the topological charge of the beam. The variation with the wavelength is more complex since absorption depends on  $\lambda$ .

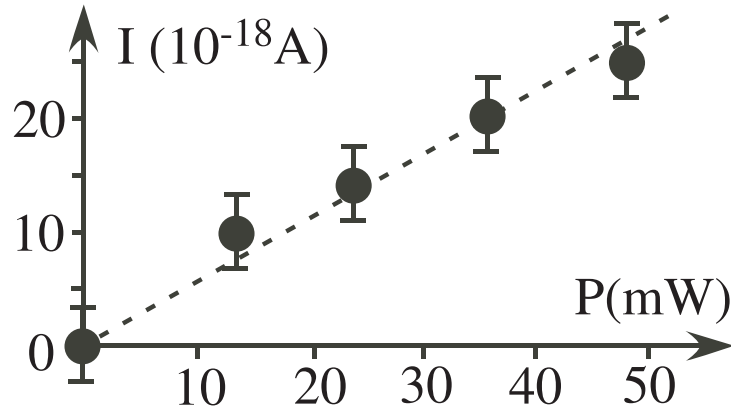
## 4. Results

### 4.1. Current versus optical power

In order to test these assumptions, we have varied the optical power for a given wavelength of  $\lambda = 532 \text{ nm}$  and a topological charge of  $\ell = 50$  (see figure 2), and we have registered the variation of the current within the copper coil. We have changed the excitation current of the laser and we have measured the optical power after the OAM beam filtering just before it impinges on the coil. The current variation is linear as expected from equation (2).

The optical torque is thus converted into a current that is registered, leading to a direct measurement of the torque. One has however to note that the currents are very weak (in the  $10^{-17} \text{ A}$  range). They correspond to around one hundred electrons per second in a section within the coil. We thus have to average the signal from the lock-in amplifier over more than 10 s to attenuate fluctuations. Anyway, the whole apparatus is still very sensitive to fluctuations. Nevertheless, for  $\ell = 50$ , it can measure torque with power as low as 10 mW.

The slope of the experimental variation of the current versus the optical power of figure 2 is  $5.2 \pm 0.3 \times 10^{-16} \text{ A W}^{-1}$ . Let us compare this value with the theoretical expression of equation (6). For



**Figure 2.** Variation of the measured current in the coil versus the optical power. The power is measured after the SLM and the 4f filtering system, just before impinging on the copper coil detector. The dotted line corresponds to a linear adjustment (so called  $R^2$  value corresponding to the fit equals 0.91). The error bars are directly shown on the figure.

$\ell = 50$ ,  $\lambda = 532$  nm,  $\eta(\lambda = 532) = 0.4$  [24],  $S = \pi R^2$ , with  $R = 3.5$  mm, i.e. in between the inner and the outer radii, one finds a slope that equals  $7.40 \times 10^{-14}$  A W $^{-1}$ , i.e. more than two orders of magnitude higher than the experimental value. Here, we have implicitly assumed in our calculations that the angular momentum transfer efficiency to the electron, apart from light absorption equals one. Where does the discrepancy come from?

It has to be noted that, in our experiment, the coil is not at all a perfect closed coil. In order to measure the current, the coil is made open and then closed with copper wires and a pico-ampere-meter. This of course implies at least two tin solders (see figure 1(b)) that strongly increases the resistance of the setup. We have measured a resistance of the total circuit (coil, solders and wires) of  $R' = 0.26 \pm 0.02 \Omega$ . Assuming a closed coil would lead to an effective resistivity of copper  $\rho_{\text{eff}}$ , for a thickness of  $h' = 35 \mu\text{m}$ , for a section of the coil  $S' = (R_{\text{out}} - R_{\text{in}})h'$  and a length of  $2\pi R$ , that equals

$$\rho_{\text{eff}} = R' \frac{S'}{2\pi R} = 2.41 \pm 0.02 \times 10^{-6} \Omega\text{m} \quad (7)$$

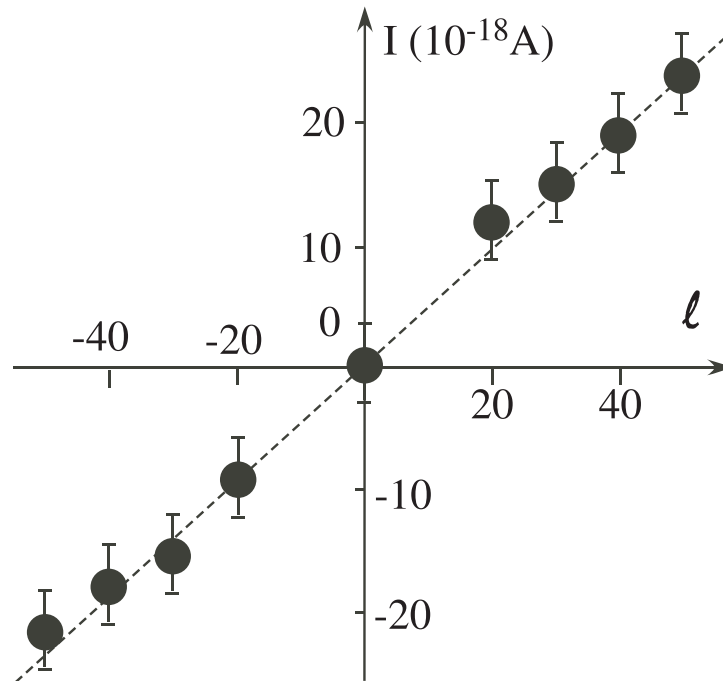
i.e. more than two orders of magnitude over the usually assumed value of the resistivity of copper  $\rho = 1.7 \times 10^{-8} \Omega\text{m}$  [30]. According to equation (4), the mean free time should also decrease by more than two orders of magnitude, leading to  $\tau = 0.16 \times 10^{-15}$  s. The current in the coil should also decrease, according to equation (6). The theoretical slope would then be  $5.0 \times 10^{-16}$  A W $^{-1}$ , in excellent agreement with the experimental slope. This also means that the OAM transfer from photons to electrons in copper is very efficient.

#### 4.2. Current versus topological charge

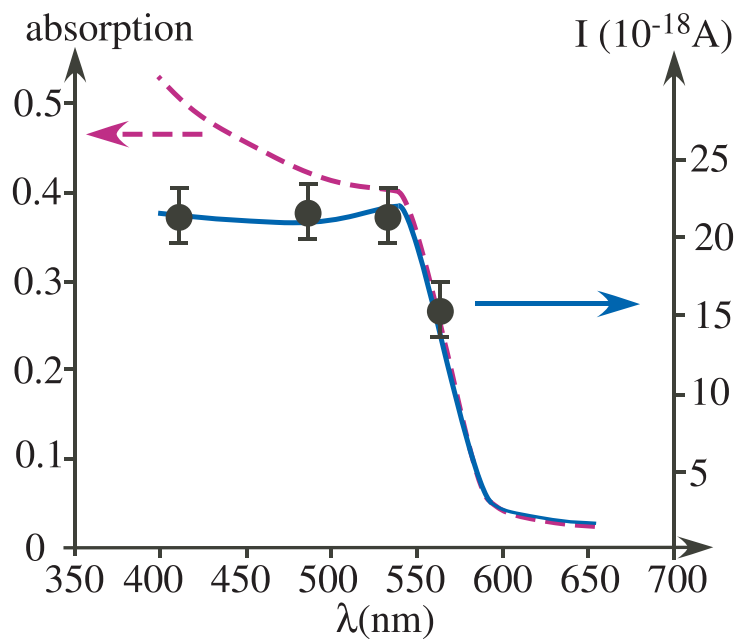
We have also varied the topological charge of the beam, keeping the optical power constant. This was performed by changing the phase hologram sent on the liquid crystal molecules of the SLM. The position of lens  $f_2$  has been also changed so that the size of the beam on the copper coil is roughly the same, whatever the  $\ell$  value. The output of the laser has to be adjusted to keep the power impinging on the coil constant. For a constant power of  $P = 50$  mW, the variation of the current versus  $\ell$  appears in figure 3. As expected, this variation is linear, in agreement with equation (6). Note that the direction of the torque could be reversed when changing the sign of the topological charge. The slope of the variation with  $\ell$  is  $0.49 \pm 0.30 \times 10^{-18}$  A, in good agreement with the theoretical value  $0.47 \times 10^{-18}$  obtained from equation (6). It means in particular that the direction of the torque as well as its magnitude could be measured with our experimental device. Knowing the optical power, the topological charge can then be deduced from equation (2).

#### 4.3. Current versus wavelength

Finally, we have changed the wavelength, keeping the topological charge and the power constant ( $\ell = 50$ ,  $P = 50$  mW). The variation of the current in the coil versus the wavelength  $\lambda$  appears in figure 4, for four different wavelengths. The dotted line corresponds to the variation of the absorption versus  $\lambda$ , extracted from the values of [24]. The solid line corresponds to equation (6), taking into account that  $\eta$  depends on  $\lambda$ . There is no adjustable parameter in this curve. The agreement between this theoretical curve and the experimental points is very good, validating our model.



**Figure 3.** Variation of the measured current versus the topological charge  $\ell$  that can be either positive or negative. The error bars are shown on the graph. The dotted line corresponds to a linear adjustment ( $R^2 = 0.92$ ).



**Figure 4.** Variation of the measured current versus wavelength (points with error bars), for an optical power of 50 mW and for a topological charge  $\ell = 50$ . The red dotted line corresponds to the absorption of the copper (extracted from [24]). The solid blue line is a theoretical curve obtained, according to equation (6), with no fitting parameter. Adapted with permission from [24] © The Optical Society.

## 5. Discussion

We have thus evidenced that the OAM of light can be converted into a current in a coil with a very high efficiency. This is the first step towards the realization of a torque meter for the light. To reach this goal, several improvements to the present experimental set-up have to be performed. The first one is related to the overall resistance of the copper coil, copper wires and coil wire soldering connections that are really too high. An *all integrated* printed circuit board directly connected to the pico-ampere-meter could be a solution. Besides, in order to decrease the effective resistivity, one may cool down the system, perhaps down to



nitrogen temperature. In addition, the geometry of the experimental device must also be optimized (inner and outer diameter of the coil, thickness of the copper coil, and copper wire lengths if any). The current detection could also be optimized with a dedicated sensitive ampere-meter.

The second improvement concerns the material to be used to transfer OAM from photons to electrons. Copper has a rather good absorption coefficient in the green-blue range of the spectrum, together with a good OAM transfer efficiency, but it is very bad in the other part of the visible spectrum and in the near infra-red. One has to find out a material with a reasonable absorption coefficient over the whole spectrum under study. This resembles the quest to find a good material for photovoltaic cells [32, 33], since the absorption efficiency over the whole solar spectrum, especially at the top of the emissivity of the Sun, is a key parameter. Perovskite or semiconductor cells could be a solution. The remaining question would then be whether optical OAM could be transferred to this kind of cells, still with a good efficiency.

## 6. Conclusion

To conclude, we have evidenced the transfer of OAM from photons to electrons in a copper coil. It manifests itself as a current in the range of tens of atto-ampere that has to be detected with a pico-ampere-meter and a lock-in amplifier. The variation of this current has been investigated versus, either the optical power, the topological charge, or the wavelength. It shows very good agreement with the theoretical predictions based on a simple model. This may pave the way towards the realization of a torque meter or a topological charge meter for optical beams carrying OAM.

However, OAM is not limited to the optical part of the electromagnetic spectrum [34, 35]. In particular, it has a growing influence in the microwave range [36, 37]. The direct determination of the topological charge may thus be of crucial interest in this part of the electromagnetic spectrum. The device we have presented here may be adapted to the case of microwaves. Nevertheless, the transfer mechanism should be different. The electrons cannot react directly at optical frequencies whereas they may respond at microwave frequencies, leading to oscillating currents and current drifts that may be easier to detect. The transfer efficiency may also be different.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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