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Vortex beam generation by spin-orbit coupling in Bloch surface waves

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32 **ABSTRACT**

33 Axis-symmetric grooves milled in metallic slabs have been demonstrated to promote the transfer of
34 Orbital Angular Momentum (OAM) from far- to near-field and vice versa, thanks to spin-orbit
35 coupling effects involving Surface Plasmons (SP). However, the high absorption losses and the
36 polarization constraints, which are intrinsic in plasmonic structures, limit their effectiveness for
37 applications in the visible spectrum, particularly if emitters located in close proximity to the metallic
38 surface are concerned. Here, an alternative mechanism for vortex beam generation is presented,
39 wherein a free-space radiation possessing OAM is obtained by diffraction of Bloch Surface Waves
40 (BSWs) on a dielectric multilayer. A circularly-polarized laser beam is tightly focused on the
41 multilayer backside by means of an immersion optics, such that TE-polarized BSWs are launched
42 radially from the focused spot. While propagating on the multilayer surface, BSWs exhibit a spiral-
43 like wavefront due to the polarization-selective coupling mechanism. A spiral grating surrounding
44 the illumination area provides for the BSW diffraction out-of-plane, by imparting an additional
45 azimuthal geometric phase distribution defined by the topological charge of the spiral structure. At
46 infinity, the constructive interference results into free-space beams with defined combinations of
47 polarization and OAM satisfying the conservation of the Total Angular Momentum, based on the
48 incident polarization handedness and the spiral grating topological charge. As an extension of this
49 concept, chiral diffractive structures for BSWs can be used in combination with surface cavities
50 hosting light sources therein.

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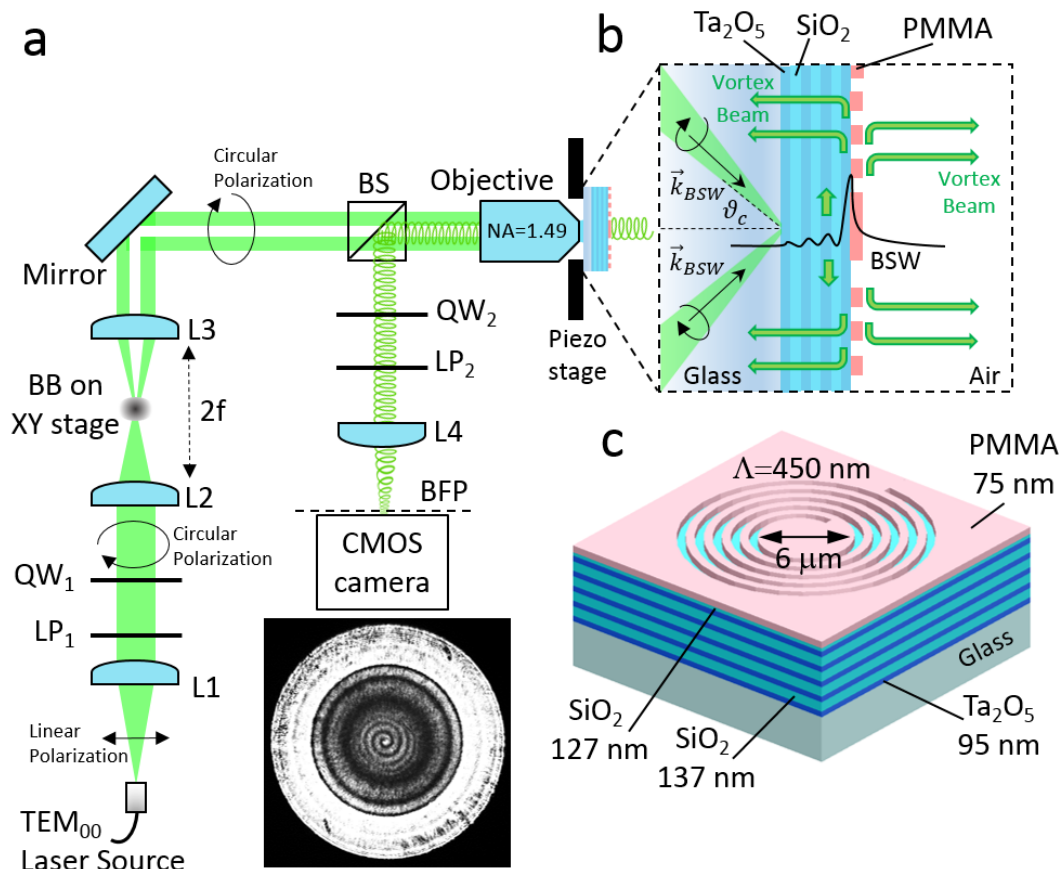
59 INTRODUCTION

60 Vortex beams represent a family of structured beams generally characterized by a phase singularity
61 along the optical axis, a doughnut intensity distribution and an azimuthally-varying phase over a beam
62 transverse cross-section [1,2]. When the polarization state is spatially inhomogeneous, the term
63 Vectorial Vortex Beams is often used [3]. From a quantum-optics perspective, each vortex beam
64 photon is provided with a quantized Orbital Angular Momentum (OAM) equal to $\hbar\ell$, where ℓ is an
65 integer indicating the topological charge of the vortex. In recent years, Vortex beams have gained an
66 increasing popularity because of several new applications into different domains such as micro-
67 particle manipulation and trapping [4-6], compact laser sources [7,8], microscopy [9,10] and optical
68 communications [11,12]. Conventional methods for producing vortex beams [13] involve the use of
69 (possibly tunable) anisotropic media such as Liquid Crystal [14,15] and q-plates [16] or hierarchically
70 structured holograms encoding proper phase functions [17-20]. More recently, metasurfaces, which
71 can be either dielectric or plasmonic, have been introduced in order to gather more degrees of freedom
72 in OAM manipulation [21,22], through the control of so-called spin-orbit coupling effects mediated
73 by the metasurface topology [23]. Metasurfaces are mainly employed as free-space beam converters,
74 which have found applications also within laser cavities [24]. The concept of beam conversion
75 through metasurfaces relies on a spatially-dependent phase manipulation of the scattered field. The
76 output vortex beams result from a coherent sum of the scattered radiation originating from different
77 portions of the surface, which is illuminated as a whole. However, this approach can be hardly
78 adopted when the input field has a limited spatial extension (as for focused beams or localized
79 coherent sources such as optical antennas or cavities), unless some mode coupling is intervening [25].
80 This is indeed the case in structured metallic films, wherein the generation of free-space vortex beam
81 carrying OAM occurs upon spin-orbit coupling and scattering/diffraction of plasmonic modes by
82 means of nano-slits [26-28], properly arranged nano-apertures [29], possibly combined with circular
83 diffraction gratings [30,31]. Such results rely on the fact that OAM possessed by surface plasmons
84 can be further manipulated and transferred to freely propagating radiation [28,32].

85 Here we propose an alternative way of producing vortex beam, by exploiting Bloch Surface Waves
86 [33,34] on dielectric multilayers as a mean to transfer energy, momentum and OAM to a free-space
87 propagating beam. Such a two-step process involves a spin-orbit conversion from a focused circularly
88 polarized beam into radially propagating BSWs and a BSW diffraction in free-space, with an
89 additional geometric phase imparted by a chiral diffraction grating. Such a BSW-based approach can
90 benefit from the multilayer low absorption that is potentially suitable for light source integration and
91 an additional degree of freedom in the polarization state of coupled BSWs, which can be either TE-
92 or TM-polarized depending on the multilayer design [35].

93 The setup and the sample structure are shown in Figure 1 and described in detail in the Methods
94 section. Briefly, in Figure 1a, a circularly polarized Gaussian CW laser beam ($\lambda=532$ nm) is expanded
95 and spatially filtered by means of a properly sized circular Beam Blocker. An oil-immersion, high
96 NA objective is back-contacted to a multilayer glass substrate, in order to focus the incoming beam
97 onto a flat area of the top surface. The multilayer is made of a stack of multiple Ta₂O₅ and SiO₂ layers,
98 topped by a 75 nm-thick PMMA film (Figure 1b,c). Thanks to the beam blocker, only focused light
99 propagating at angles larger than the glass/air critical angle θ_c can reach the sample. A fraction of the
100 incoming power is thus available for coupling to BSWs, provided that wavelength, momentum and
101 polarization matching conditions are fulfilled, as indicated by the BSW dispersion curve for TE-
102 polarization [36]. Since the coupling mechanism is polarization-sensitive and the incident electric
103 field is circularly polarized, BSWs are spreading radially from the focused spot area, with an
104 accumulated phase delay that is linearly varying with the azimuthal angle of the propagation direction.
105 As a result, a BSW propagating radially on the multilayer surface is obtained, with a peculiar spiral-
106 like wavefront profile (see Supporting Information), analogous to plasmonic vortices [26].
107 Surrounding the flat coupling region, an axis-symmetric diffractive grating is etched in the PMMA
108 layer. The grating operates as an outcoupler, by diffracting BSWs out-of-plane in both substrate
109 (glass) and cladding (air) media, along a direction close-to-normal to the sample surface (order of
110 diffraction $n=-1$) [37]. Depending on the grating shape (e.g. circular or spiral-like), an additional

111 geometrical phase profile can be imparted to the diffracted radiation. In previous applications, this
 112 feature has been exploited for steering the diffracted beam [38,39]. The outcoupled power is then
 113 collected by the same high-NA objective and Fourier-transformed before being imaged on the camera
 114 plane. A linear polarizer and a quarter-wave plate allow for a polarization analysis on the collected
 115 images. If the beam blocker is removed, an interference pattern as shown in Figure 1 can be obtained.
 116 In this exemplary case, the spiral-shaped interference fringes result from the superposition of a
 117 diffracted vortex beam (OAM number $\ell = 1$) and light reflected from the sample surface [32].



118
 119 **Figure 1.** a) Sketch of the experimental setup. L_{1-4} Plano-Convex lenses, $LP_{1,2}$ Polarizers, $QW_{1,2}$
 120 Quarter-wave Plates, BB Beam Blocker, BS Beamsplitter, BFP Back Focal Plane. In the exemplary
 121 BFP image, an interference pattern is shown, due to the superposition of a diffracted vortex beam and
 122 a reflected spherical wave from the sample surface. No Beam Blocker has been used in this case. b)
 123 Detailed view of the BSW coupling and diffraction mechanism. Illumination is provided by means
 124 of a beam-blocked circularly polarized laser beam focused through an oil immersion objective, such
 125 that the minimum incidence angle is slightly above the critical angle θ_c , in order to match the BSW
 126 coupling conditions. c) Sketch of the multilayer structure with an exemplary spiral diffraction grating
 127 fabricated in PMMA on top (not to scale).

128 RESULTS AND DISCUSSION

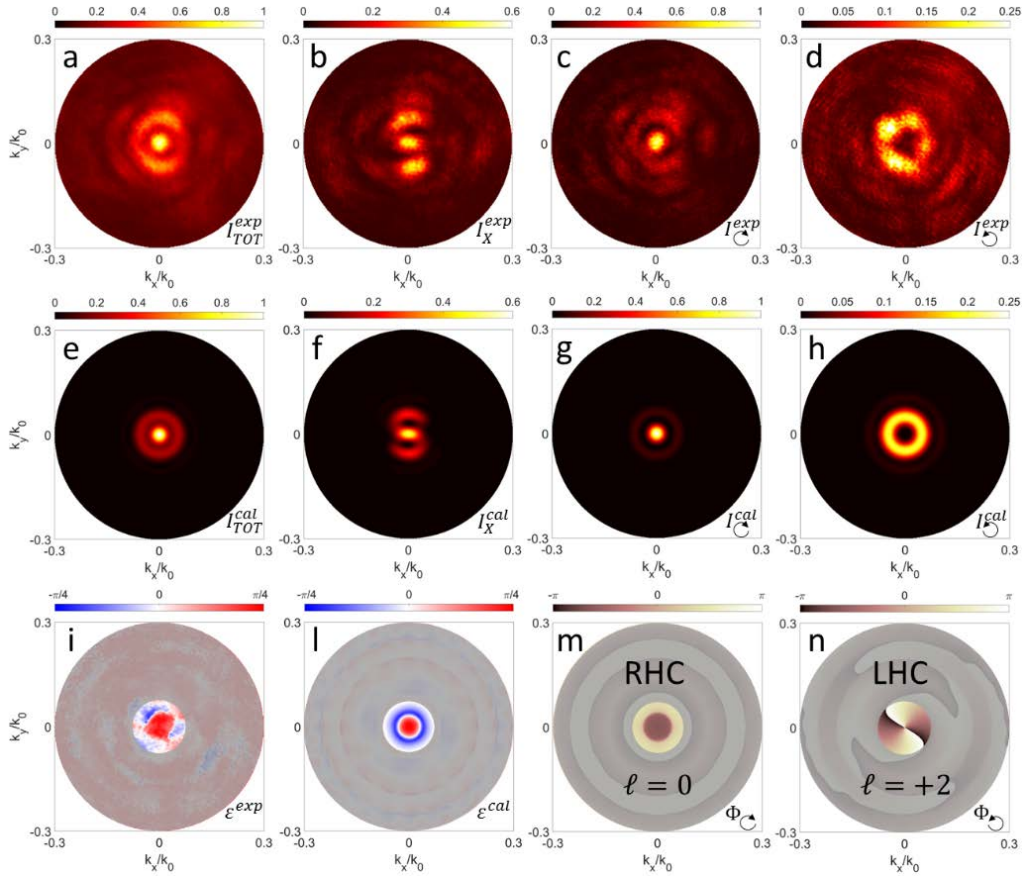
129 In this section, experimental results are presented related to (i) a circular-symmetric annular grating
130 with topological charge $m=0$, (ii) a single-arm spiral grating, (iii) a double-arm spiral grating. In the
131 last two cases, both handedness of the incident polarization are considered, namely Right-Handed
132 Circular (RHC) and Left-Handed Circular (LHC) polarizations, such that the incident beam Spin
133 Angular Momentum (SAM) and the grating topological charge can have either equal or opposite sign.
134 In order to evaluate the polarization state of the diffracted light, the polarization ellipse
135 parameter $\varepsilon(k_x, k_y) = \frac{1}{2} \arg(\sqrt{S_1^2 + S_2^2} + iS_3)$ is calculated across the BFP, where S_1 , S_2 and S_3 are
136 the Stokes parameters [40]. Right-Handed Circular (RHC), Left-Handed Circular (LHC) and Linear
137 Polarizations (LP) correspond to $\varepsilon_{RHC} = \frac{\pi}{4}$, $\varepsilon_{LHC} = -\frac{\pi}{4}$ and $\varepsilon_{LP} = 0$ respectively. Polarization-
138 filtered raw images and Stokes parameter distributions for the structures considered here are shown
139 in the Supporting Information.

140 A numerical 3D model based on a commercial Finite-Difference Time-Domain (FDTD) solver
141 (Lumerical Inc.) is used to support the interpretation of the experimental observations. In order to
142 mimic the focused circularly polarized beam underlying the BSW coupling, a pair of (coherent) linear
143 orthogonal dipoles laying on the multilayer plane and oscillating with a $\frac{\pi}{2}$ relative phase delay are
144 introduced (see Supporting Information Movie S2). Further details on the validity of this model are
145 provided in the Methods section.

146 **Circular Outcoupler ($m=0$).** In this configuration, a RHC circular polarization ($\varepsilon = \frac{\pi}{4}$) is employed
147 to couple BSWs that are then diffracted. As shown in Figure 2a,e, the total intensity collected on the
148 BFP exhibits a maximum at $k_x=k_y=0$, corresponding to a constructive interference condition for light
149 traveling along a direction perpendicular to the multilayer surface. A linear-polarization filtering
150 reveals the presence of a pair of spiral-like arms spreading from the central maximum that rotate as
151 the polarization analyser is rotated (in Figure 2b,e the measured and calculated intensity of the x-
152 component of the diffracted light are presented). Without the polarization filter, the spiral-like arms

153 merge together to form a ring surrounding the central maximum. When polarization-projected onto a
 154 RHC polarization state, the intensity pattern has still a maximum in the BFP center (Figure 2c,g),
 155 while a weak ring is obtained for a projection onto a LHC polarization state (Figure 2d,h). A
 156 comparison between the distributions for the measured and the calculated parameter $\varepsilon(k_x, k_y)$ on the
 157 BFP indicates that the central maximum is substantially RHC polarized, i.e. $\varepsilon(0,0) \cong \frac{\pi}{4}$, while the
 158 outer ring is LHC polarized, i.e. $\varepsilon(0,0) \cong -\frac{\pi}{4}$ (Figure 2i,l).

159 By enforcing the conservation of the Total Angular Momentum J , which also takes into account the
 160 topological charge m imparted by the diffraction grating, the following equation applies: $\sigma_i + m =$
 161 $1 + 0 = \sigma_o + \ell$, where σ_o is the output SAM number and ℓ is the corresponding OAM number. The
 162 solution to this equation is not unique. In particular, two SAM-OAM configurations are possible: a
 163 RHC beam preserving the input polarization and carrying zero OAM, i.e. $\sigma_o = +1$ and $\ell = 0$, and a
 164 doughnut LHC beam with a reverse polarization, with $\sigma_o = -1$ and OAM with $\ell = +2$. The two
 165 beams are partially overlapped. This observation is supported by the phase distribution calculated for
 166 the RHC and the LHC polarized fields presented in Figure 2m,n: a flat wavefront with constant phase
 167 is found for the RHC beam ($\ell = 0$) and a spiral wavefront with two 2π discontinuities for the LHC
 168 beam ($\ell = +2$).

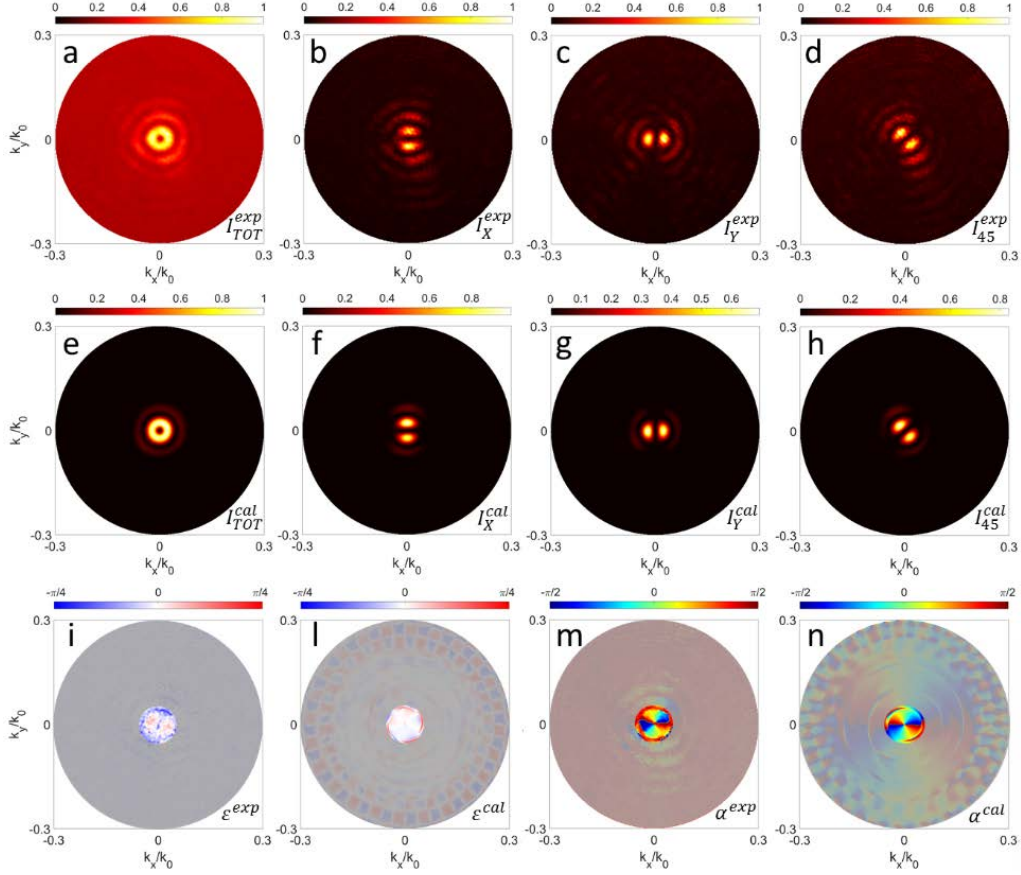


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170 **Figure 2.** BFP Diffraction patterns from a circular outcoupler ($m = 0$). Incident polarization is RHC.
 171 a,e) experimental and calculated total intensity showing a central spot surrounded by a weak outer
 172 ring; b,f) experimental and calculated x-polarized intensity; c,g) experimental and calculated RHC
 173 intensity showing a central spot; d,h) experimental and calculated LHC intensity showing a doughnut
 174 shape; i,l) experimental and calculated polarization ellipse parameter $\varepsilon(k_x, k_y)$ with the sign reversal
 175 from the inner area to the outer ring; m) calculated phase of the diffracted field with RHC polarization,
 176 showing a constant distribution; n) calculated phase of the diffracted field with LHC polarization,
 177 showing two 2π discontinuities.

178

179 **Spiral Outcoupler ($m = -1$).** BSWs are first coupled with an input RHC polarization ($\sigma_i = +1$)
 180 and made interacting by a spiral grating with opposite handedness ($m = -1$). The corresponding
 181 intensity pattern is shown in Figure 3a,e.



182

183 **Figure 3.** BFP Diffraction patterns from a 1-arm spiral outcoupler ($m = -1$). Incident polarization
 184 is RHC. a,e) experimental and calculated total intensity showing a doughnut shape; b,f) experimental
 185 and calculated x-polarized intensity; c,g) experimental and calculated y-polarized intensity; d,h)
 186 experimental and calculated 45°-polarized intensity; i,l) experimental and calculated polarization
 187 ellipse parameter $\varepsilon(k_x, k_y)$ indicating a substantially linear polarization state $\varepsilon \cong 0$; m,n)
 188 experimental and calculated ellipse parameter $\alpha(k_x, k_y)$ indicating an azimuthal orientation of the
 189 electric field.

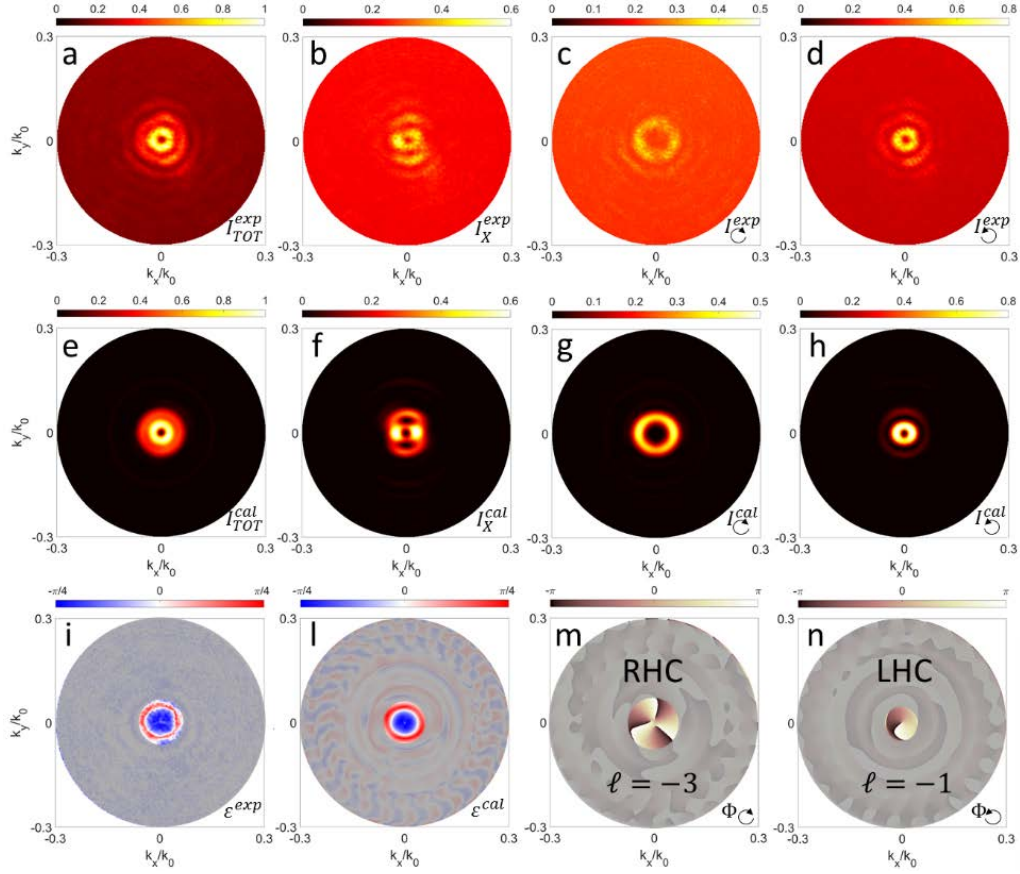
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191 The phase delay profile imparted by the diffractive structure onto the diffracted BSWs results in a
 192 destructive interference such that a zero-intensity phase singularity is produced at $k_x=k_y=0$. When
 193 filtered with the linear polarizer LP₁ (e.g. oriented along the x, y or 45° direction), two-lobe patterns
 194 are found, whose orientation is perpendicular to the analyser transmission axis (Figures 3b-d).
 195 Calculated intensity patterns are in good agreement with the experimental observations (Figures 3f-
 196 h). The distribution of the parameter $\varepsilon(k_x, k_y)$ shows a substantially linear polarization corresponding
 197 to the doughnut ($\varepsilon \cong 0$) (Figures 3i,l). The uniformity of the polarization orientation is evaluated by

198 extracting the parameter $\alpha(k_x, k_y) = \frac{1}{2} \text{arg}(S_1 + iS_2)$, which provides the local orientation of the
 199 polarization ellipse (almost a line, in this case) across the BFP [40]. In Figures 3m,n both the
 200 experimental and the calculated distributions for $\alpha(k_x, k_y)$ indicate that the substantially linear
 201 polarization follows an axis-symmetric distribution such that the electric field is azimuthally oriented
 202 about the beam axis in $k_x = k_y = 0$. In this case, the J conservation rule reads as $\sigma_i + m =$
 203 $1 - 1 = \sigma_o + \ell = 0$, leading to an output SAM number $\sigma_o = 0$ and an OAM $\ell = 0$, which is
 204 consistent with the observed azimuthal polarization state of the output beam.

205 When the illumination polarization is switched to LHC ($\sigma_i = -1$) the input SAM and the grating
 206 topological charge possess the same sign. The overall intensity pattern having a doughnut shape is
 207 presented in Figure 4a,e. At a closer look, the output results from the superposition of a pair of ring-
 208 shaped beams, which are non-interfering because of their orthogonal polarizations. A weak outer ring
 209 (Figure 4c,g) is imaged upon RHC filtering, while an intense inner ring (Figure 4d,h) is obtained
 210 upon LHC filtering. The experimental and the calculated distributions for $\varepsilon(k_x, k_y)$ (Figure 4i,l)
 211 confirm that the polarization state of the two beams is still substantially circular. However, a reversal
 212 of handedness from LHC to RHC can be found while moving from the inner ring toward the outer.

213 The two partially overlapped beams must satisfy the J conservation rule, i.e. $\sigma_i + m =$
 214 $-1 - 1 = \sigma_o + \ell = -2$. A first solution to this equation is represented by a LHC polarized beam
 215 having the same SAM number as the incident radiation $\sigma_o = -1$ and OAM $\ell = -1$. An orthogonal
 216 solution is a RHC polarized beam having a reversed SAM $\sigma_o = +1$ and OAM $\ell = -3$. The
 217 topological charge of the diffracted vortex beams can be directly appreciated from the calculated
 218 phase distributions of the RHC and LHC polarized beams (Figure 4m,n), exhibiting three and one 2π
 219 discontinuities respectively, on the BFP.

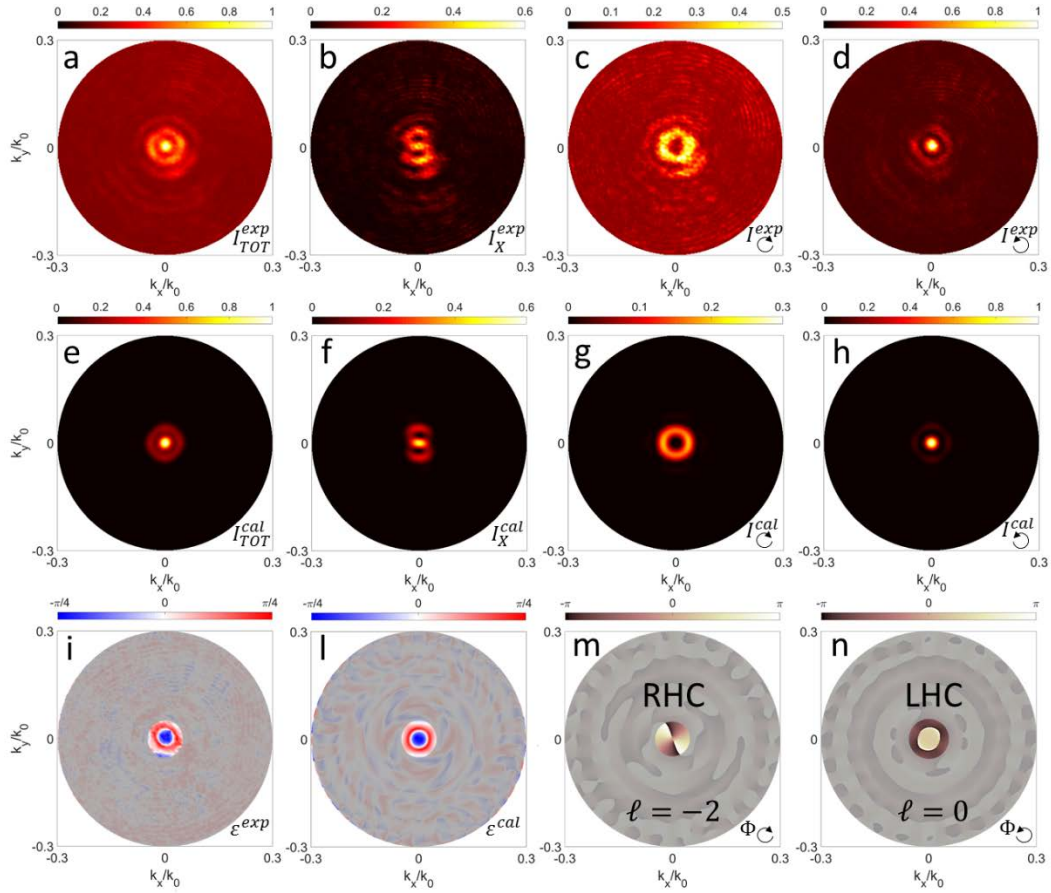


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221 **Figure 4.** BFP Diffraction patterns from a 1-arm spiral outcoupler ($m = -1$). Incident polarization
 222 is LHC. a,e) experimental and calculated total intensity showing a superposition of an inner and an
 223 outer ring-shaped patterns; b,f) experimental and calculated x-polarized intensity; c,g) experimental
 224 and calculated RHC intensity, distributed according to the outer ring; d,h) experimental and calculated
 225 LHC intensity; distributed according to the inner ring; i,l) experimental and calculated polarization
 226 ellipse parameter $\varepsilon(k_x, k_y)$ indicating a substantially circular polarization with handedness reversal
 227 from the inner to the outer ring; m) calculated phase of the diffracted field with RHC polarization,
 228 showing three 2π discontinuities; n) calculated phase of the diffracted field with LHC polarization,
 229 showing one 2π discontinuity.

230

231 **Spiral Outcoupler ($m = -2$).** As in the previous configuration, an incident RHC polarization ($\sigma_i =$
 232 $+1$) is first considered. The overall intensity shown in Figure 5a,e is obtained as the superposition of
 233 a weak outer ring and a brighter central spot. Both patterns can be individually imaged by operating
 234 a polarization filtering through a RHC state (Figure 5c,g) and a LHC state (Figure 5d,h), respectively.



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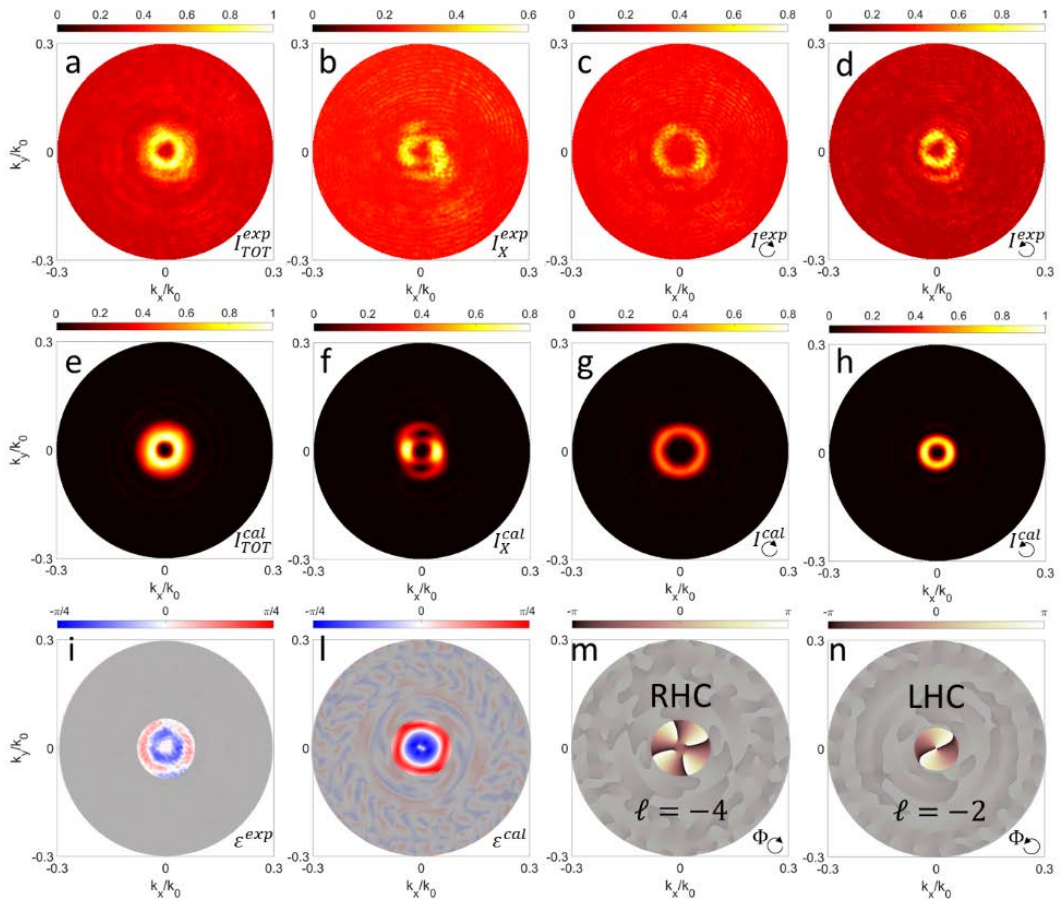
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Figure 5. BFP Diffraction patterns from a 2-arms spiral outcoupler ($m = -2$). Incident polarization is RHC. a,e) experimental and calculated total intensity, given by the superposition of a central spot and a weaker outer ring; b,f) experimental and calculated x-polarized intensity; c,g) experimental and calculated RHC intensity, distributed according to the weak outer ring; d,h) experimental and calculated LHC intensity, distributed according to the bright central spot; i,l) experimental and calculated polarization ellipse parameter $\varepsilon(k_x, k_y)$ indicating a substantially circular polarization, with handedness reversal from the central spot to the outer ring; m) calculated phase of the diffracted field with RHC polarization, showing two 2π discontinuities; n) calculated phase of the diffracted field with LHC polarization, showing a uniform phase distribution.

The distribution of the parameter $\varepsilon(k_x, k_y)$ indicates that the polarization is substantially circular across the pattern. However, the bright central spot shows a LHC polarization state, which is reversed with respect to the incident radiation (Figure 5i). Furthermore, the outer weak ring maintains a LHC polarization, as the illumination (Figure 5l). The conservation of the momentum J leads to $\sigma_i + m = +1 - 2 = \sigma_o + \ell = -1$, which has the following two solutions associated to the observed beams:

251 $\sigma_o = +1$ (RHC) and $\ell = -2$; $\sigma_o = -1$ (LHC) and $\ell = 0$. The calculated phase distributions are
 252 consistent with the Total Angular Momentum algebra, since the RHC beam has a vortex wavefront
 253 with two 2π discontinuities, while the LHC beam has a flat wavefront (Figure 5m,n). A constant
 254 phase is also consistent with the existence of a central maximum at $k_x = k_y = 0$ for the LHC beam.
 255 For a LHC polarization ($\sigma_i = -1$) a phase singularity is produced on the optical axis, and the overall
 256 intensity pattern (Figure 6a,e) results from the superposition of a LHC polarized inner ring (Figure
 257 6c,g) and a RHC polarized outer ring (Figure 6d,h).



258
 259 **Figure 6.** BFP Diffraction patterns from a 2-arm spiral outcoupler ($m = -2$). Incident polarization
 260 is LHC. a,e) experimental and calculated total intensity; b,f) experimental and calculated x-polarized
 261 intensity; c,g) experimental and calculated RHC intensity; d,h) experimental and calculated LHC
 262 intensity; i,l) experimental and calculated polarization ellipse parameter $\epsilon(k_x, k_y)$; m) calculated
 263 phase of the diffracted field with RHC polarization showing four 2π discontinuities; n) calculated
 264 phase of the diffracted field with LHC polarization, showing two 2π discontinuities.

265

266 Measured and calculated $\varepsilon(k_x, k_y)$ show the handedness reversal occurring when departing from the
 267 optical axis toward larger propagation angles, wherein the inner ring preserves the same polarization
 268 as the incident radiation (Figure 6i,l). From the conservation of the momentum J , we have: $\sigma_i + m =$
 269 $-1 - 2 = \sigma_o + \ell = -3$, which has the following solutions: $\sigma_o = +1$ (RHC) and $\ell = -4$; $\sigma_o = -1$
 270 (LHC) and $\ell = -2$. In this case, both beams exhibit a phase vorticity, with four 2π discontinuities
 271 for the RHC (Figure 6m) state and two 2π discontinuities for the LHC state (Figure 6n).

272

273 CONCLUSION

274 To conclude, a new mechanism for the generation of vectorial vortex beams has been presented, based
 275 on spin-orbit interactions involving coupling and diffraction of BSWs. Generally speaking, this kind
 276 of effects relies on the coherence characteristics of the radiation involved. For this reason, we
 277 employed a laser beam as an external free-space radiation for coupling BSWs that are subsequently
 278 diffracted, with an imparted geometrical phase. Several combinations of polarization states and OAM
 279 are obtained, as summarized in Table 1. Further options for vortex beam generation carrying OAM
 280 with other polarization configurations can be possibly produced by means of multilayers supporting
 281 TM-polarized, in addition to TE-polarized BSWs [41].

	Grating Topological Charge m	$m = 0$	$m = -1$	$m = -2$
Incident SAM σ_i				
$\sigma_i = +1$		$\sigma_o = -1 \ \& \ \ell = +2$ $\sigma_o = +1 \ \& \ \ell = 0$	$\sigma_o = 0 \ \& \ \ell = 0$	$\sigma_o = -1 \ \& \ \ell = 0$ $\sigma_o = +1 \ \& \ \ell = -2$
$\sigma_i = -1$		$\sigma_o = -1 \ \& \ \ell = 0$ $\sigma_o = +1 \ \& \ \ell = -2$	$\sigma_o = -1 \ \& \ \ell = -1$ $\sigma_o = +1 \ \& \ \ell = -3$	$\sigma_o = -1 \ \& \ \ell = -2$ $\sigma_o = +1 \ \& \ \ell = -4$

282 **Table 1.** Summary of the SAM-OAM combinations obtained by diffraction of BSWs coupled from
 283 either RHC or LHC polarized incident light.

284

285 The numerical model developed here suggests that the presented approach is likely to work regardless
 286 of the coupling mechanism for BSWs. For example, in the perspective of advanced engineered light

287 sources for free-space applications, BSWs can be launched from a single emitter on the multilayer
288 surface by virtue of near-field interactions (so-called BSW-coupled emission) [42,43]. Then, chiral
289 diffractive structures can be used as outcouplers surrounding single sources or even planar BSW
290 cavities (e.g. as described in ref. [44]) hosting light sources within. Provided the coherence
291 requirements for the BSW-coupled radiation leaking out of the cavity are satisfied, the diffraction
292 mechanism for free-space vortex generation remains as reported in the text above. While nanocavities
293 can be chiral themselves, with a handedness-depending LDOS [45], it has been recently shown that
294 chiral plasmonic structures can foster sources located on their surface to radiate according to a specific
295 circular polarization handedness [46]. These strategies provide an unprecedented degree of control
296 on the polarization state of the emitted light. The use of BSWs as a mean for coupling and transferring
297 energy from sources to free-space, mediated by chiral diffractive gratings, can contribute to enhance
298 the performance of purely plasmonic nanostructures, which are often limited by the strong absorption
299 occurring at visible frequencies.

300

301 **METHODS**

302 **Experimental setup.** A TEM₀₀ doubled-frequency Nd:YAG laser beam (GEM, Laser Quantum) is
303 collimated (L₁) and transmitted through a first polarization-control box, consisting of a linear
304 polarizer LP₁ and a quarter wave plate QW₁. Circular polarization states with both handedness (RH
305 and LH) are generally produced. A beam blocker is introduced in order to spatially filter the laser
306 beam, such that an illumination above the glass/air critical angle θ_c is provided only. The incoming
307 beam is focused onto a flat area on the top surface of the multilayer through a $NA = 1.49$ objective
308 (Nikon Apo TIRF 1003) that is back-contacted to the glass substrate of the sample. The sample holder
309 is mounted on a 3-axis piezo stage. When measuring the diffraction patterns from the spiral gratings,
310 the excitation laser is accurately focused onto the geometric center of the diffraction gratings.
311 Diffracted light on the glass side is collected by the same objective and directed toward the collection
312 arm of the setup, after passing through a 50/50 beam splitter. A second polarization-control box

313 consisting of a quarter wave plate QW_2 and a linear polarizer LP_2 filters the outgoing wave onto the
314 desired polarization state (RHC, LHC or LP). Subsequently, the lens L_4 images the BFP of the
315 objective onto a CMOS camera (Thorlabs HR-CMOS DCC3260M). With no Beam Blocker, an
316 interference pattern appears in the BFP image, due to the superposition of the light reflected by the
317 multilayer inside the light cone ($NA \leq 1$) with the diffracted BSW patterns, eventually carrying
318 OAM. As a result, spiral-like interference fringes can be observed depending on the OAM number ℓ ,
319 as shown in Figure S3 [32].

320 **Sample fabrication.** The 1DPC consists of a dielectric multilayer made of a stack of Ta_2O_5 (high
321 refractive index) and SiO_2 (low refractive index) layers, deposited on a glass coverslip (150 μm
322 thickness) by plasma ion-assisted deposition under high vacuum conditions (APS904 coating system,
323 Leybold Optics). The stack sequence is substrate- $[Ta_2O_5-SiO_2]_x-Ta_2O_5-SiO_2-PMMA$ with 15 layers
324 in total, including PMMA. The Ta_2O_5 layer (refractive index $n_{Ta_2O_5}=2.08$) is 95 nm thick, the SiO_2
325 layer (refractive index $n_{SiO_2}=1.46$) is 137 nm thick. The top SiO_2 layer on top of the stack is 127 nm
326 thick. On top of the structure a 75 nm thick layer of PMMA is spun for pattern fabrication
327 ($n_{PMMA}=1.48$). Chiral diffractive structures are fabricated by electron beam lithography.

328 **Numerical modeling.** Numerical modeling is performed using the Finite-Difference Time-Domain
329 method in the Lumerical Inc. software. In order to mimic the focused circularly polarized light
330 coupling to BSWs, a pair of orthogonal dipolar emitters are positioned at the geometric center of the
331 spiral grating. More specifically, the emitters are placed 10 nm above the PMMA layer, with the
332 dipole momentum laying parallel to the multilayer surface, such that the TE polarization of the BSW
333 can be matched. The two oscillators are phase-shifted by $\pm \pi/2$. In this way, thanks to a near-field
334 interaction, part of the radiated energy from the dipoles is transferred to BSWs (BSW-coupled
335 emission). As shown in Figure S1 and Supporting Movie S2, resulting BSWs are radially propagating,
336 with a spiral wavefront due to the time-varying polarization matching conditions of the field given
337 by the coherent sum of the radiation from the two dipoles.

338 The diffraction gratings are modeled as circular or spiral grooves in the PMMA layers, with a spatial
339 period $\Lambda=450$ nm. The total simulation region has dimensions $(15 \times 15 \times 2.6)$ μm^3 . Boundary
340 conditions are set as perfectly matched layers. The smallest mesh size is 23 nm. The electromagnetic
341 near-field is collected using a spatial monitor over a plane 20 nm above the PMMA layer. A near-to
342 far-field projection technique is applied to calculate the field at a distance of 1 m from the structure,
343 on the air side. A cylindrical Perfect Electric Conductor, placed 50 nm above the dipole sources, have
344 been introduced in order to avoid the direct free-space emission from the sources, which could
345 produce interference with the BSW-diffracted radiation we want to investigate. This metallic plate
346 mimic the role of the Beam Blocker in the experimental setup. With this arrangement, only the air-
347 side far-field patterns are calculated. However, as the propagation angles of the diffracted beams (with
348 respect to the multilayer normal) are very small, the refraction effects are negligible and the far-field
349 patterns are expected to be similar to those on the glass substrate side.

350

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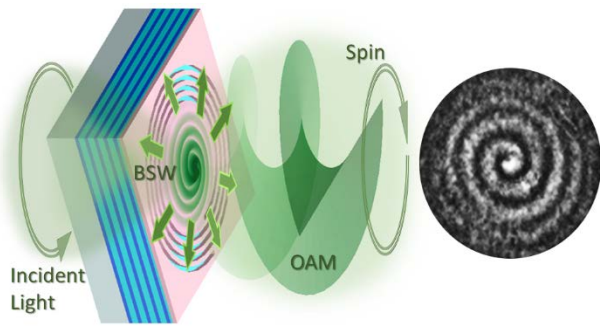
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475 **GRAPHICAL TOC ENTRY**



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