Q-plates for Switchable Excitation of Fiber OAM Modes

P. Gregg[1], M. Mirhosseini[2], A. Rubano[3], L. Marrucci[3], E. Karimi[4], R. Boyd[2,4], S. Ramachandran[1]
[1]Boston University, 8 Saint Mary's St, Boston, MA 02215, USA
[2]Institute of Optics, University of Rochester, Rochester, NY 14627, USA
[3]Dipartimento di Fisica, Università di Napoli Federico II, MSA, via Cintia, 80126 Napoli, Italy
[4]Department of Physics, University of Ottawa, 25 Templeton, Ottawa, Ontario, K1N 6N5 Canada
Author e-mail address:sidr@bu.edu

Abstract: We demonstrate that a $|q|$=1/2 plate plus polarization optics can tunably excite all linear combinations of $|l|$=1 fiber OAM modes with up to ~30 dB purity, enabling switch fabrics in fiber-OAM networks and disentangling of degenerate mode mixing effects in long fibers.
OCIS codes: (050.4865) Optical vortices, (060.6042) Multiplexing, (260.6042) Singular optics, (260.5430) Polarization.

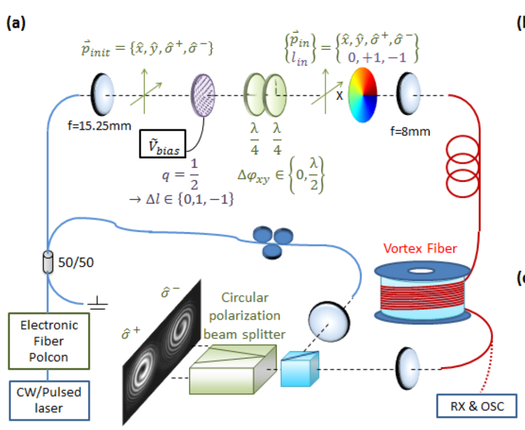
Orbital angular momentum (OAM) modes [1,2,3] in fibers have recently gained attention for increasing the dimensionality of alphabets used in space-division multiplexing (SDM) applications [4]. Methods to (de)multiplex such channels currently include spatial light modulators (SLMs) [4], mode sorters [5], and integrated photonic devices [6]. Such devices typically generate OAM modes of free space, which are considered sufficient for coupling into fiber modes, because fiber and free-space OAM modes have similar phase and polarization distributions.

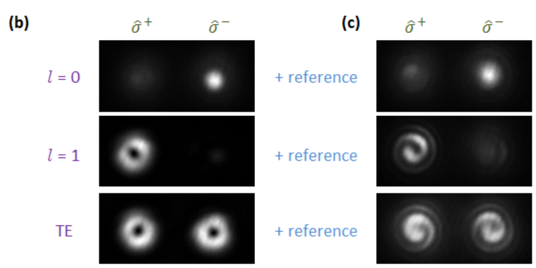
However, fiber OAM modes differ from their free-space counterparts in their degeneracies, which has implications for mitigating mode mixing effects or building switchable networks. Whereas all four free-space OAM modes of given $|l|$ are degenerate, allowing turbulence compensation [7] or data exchange [8] with SLMs or other free-space devices, fiber OAM modes come in degenerate pairs of opposing polarizations and opposite signs of l, given by (for $|l|$ = 1):

$$OAM_{1,m}^{\pm} = (\hat{\sigma}^{\pm} e^{\pm i\varphi}) F_m(r) e^{i\beta_{OAM} z} \quad (1)$$

where $\hat{\sigma}^{\pm}$ are orthogonal (circular) polarizations, F_m is the field distribution of radial mode order m (hereafter assumed 1), and β_{OAM} is the wave-vector of the OAM modes. This two-fold degeneracy parallels the polarization degeneracy in single mode fiber (SMF) and it is well known that polarization controllers (polcons) can be realized with free-space wave-plates *or* fiber loops to switch or control polarization. We have shown that loops of OAM-fiber can act as polcons to "unwind" degenerate state coupling for $|l|$ = 1 [9], but fiber loops may be inefficient for higher l [2], cannot be used in a multiplexed fashion for several OAM modes simultaneously, and cannot be controlled at high speeds.

Here we show that *q*-plates, which couple the spin and orbital angular momentum of light [10], offer the ability to create exactly such superpositions. Hence, we demonstrate switching between OAM fiber modes, creation of any combination of the $|l|$=1 OAM modes of fiber with up to ~30-dB purity with respect to other, parasitic mode groups, and the ability to disentangle OAM mode coupling in fiber. Such low input-coupling crosstalk is a necessary condition for digital signal processing-free SDM in which OAM modes are independent information carriers.





(d)

Excited\Meas	l=0	TE	OAM	TM	LP_{02}/LP_{21}
l=0	-	-24.6	-21.0	-24.2	-29.5
TE	-20.4	-	-19.1	-19.1	-13.8*
OAM	-22.9	-22.1	-	-18.8	-19.1
TM	-20.9	-29.9	-19.1	-	18.1

Fig. 1 (a) Light with uniform polarization set by the electronic polcon passes through the *q*-plate, which imparts a Δl of 0 or ±1, followed by two rotating quarter-wave plates. The desired superposition of states with $|l|$=0 or $|l|$=1 is focused into the vortex fiber. 50/50 tap provides a reference beam for interference. (b) Fiber output and (c) interference with a reference beam at 1530nm after 300m of vortex fiber for different launch conditions. (d) Input coupling MPI. Each row indicates the same desired mode. LP_{02} and LP_{21} exist at 1530nm but are inaccessible with the q= –1/2 plate and are considered parasitic.*MPI of TE into LP02/LP21 not resolvable below 13.8dB due to detector impulse response.

A q-plate of topological charge q performs the following linear transformation (neglecting a global phase factor):

$$q \cdot (A\hat{\sigma}^{+} + B\hat{\sigma}^{-}) = A\hat{\sigma}^{-}e^{i2q\varphi} + B\hat{\sigma}^{+}e^{-i2q\varphi} \qquad (2)$$

that is, a q-plate imparts angular momentum $2q$, with sign opposite to the polarization of the incoming beam. This exactly mirrors the OAM mode degeneracy in fiber. Thus, by controlling the polarization incident to the q-plate by tuning a fiber polcon (see Fig. 1), an arbitrary superposition of states in (1) may be excited. For $q = -1/2$, or alternatively q=1/2 followed by a half-wave plate, these devices in series can access any superposition of $OAM^{\pm}$. The half-wave plate is realized here with two quarter-wave-plates in series, allowing for switchable action between no retardance, and half-wave retardance. Similarly, the TE and TM modes can be generated with $A=\pm B$ and a q= 1/2 plate. l = 0 excitation is achieved by tuning the bias of the q-plate to yield λ retardation, preserving the input beam's mode and polarization [11]. Figure 1b shows experimental images of the output after 300m of vortex fiber [1] sorted by $\hat{\sigma}^{+}$ and $\hat{\sigma}^{-}$, for different launch conditions using a CW laser. As expected, if the fiber exhibits negligible mode coupling, when an $OAM^{\pm}$ mode is excited, we observe a bright ring in only one polarization. Inclusion of a reference beam (Fig. 1c) reveals phase: $OAM^{\pm}$ modes show spirals with a handedness that matches spin. Quantitative measurements (Fig. 1d) of the mode purities, conducted with time-of-flight measurements using a pulsed laser and fast detector and oscilloscope, indicate the ability to achieve mode purities of at least -18dB, and as high as 29.9 dB. Coupling losses at 1530nm were 3.1dB for the fundamental modes, and 2.4dB for the $OAM^{\pm}$ modes, of which 1.4dB is intrinsic q–plate loss, and the remainder is from beam imperfections or size mismatches.

Having demonstrated pure mode excitation with q-plates, we excite linear combinations of degenerate OAM modes to disentangle degenerate state-mixing effects expected in long length fibers (Fig. 2). If the input polarization to the q=−1/2 plate is $\hat{\sigma}^{\mp}$, the fiber output is a pure $OAM^{\pm}$, as before (Fig 2a). Once this fiber is subject to bends and twists, degenerate state coupling occurs, yielding an OAM mode in both polarizations (Fig. 2b). However, since the fiber and q-plate span the same set of OAM modes, introducing a mode of a specific elliptical polarization to the q-plate, yields, after fiber mode-mixing, the desired pure OAM^{+} or OAM^{-} (Fig. 2c).

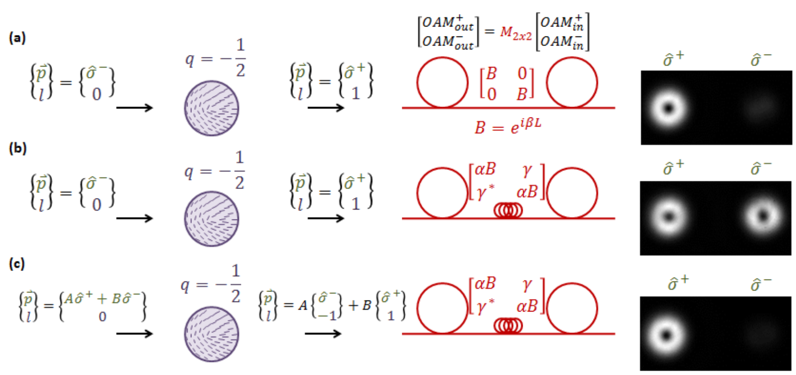


Fig. 2 OAM transmission schematic and experimental results, using a q=−1/2 plate, in the case of (a) a fiber which maintains OAM states, (b) a fiber which mixes degenerate OAM states according to some mixing coefficient, γ, such that $|\gamma|^2+|\alpha|^2=1$, and (c) a fiber which mixes degenerate OAM states, but in which said coupling is compensated for, by tuning the input state via polarization control.

In summary, a setup comprising a q-plate and two polarization controllers not only allows 18-30dB pure creation of $|l|$=1 OAM modes in fibers, it also enables creating linear combinations of these modes, hence facilitating (a) remote switching between the modes, possibly at ~GHz speeds, by tuning polcons before the transmission fiber alone and (b) disentangling of degenerate state mixing that may be unavoidable. Disentangling the effects of the fiber propagation is functionality unique to fiber-bend induced polcons and the q-plate system we demonstrate here. Between them, the q-plate system is preferable, because it is scalable with the number of OAM modes of fiber, and facilitates fast switching. Thus, the q-plate excitation scheme could play a role as vital as the polarization controller for SMF, in OAM communications networks that can also incorporate switch fabrics based on OAM modes.

[1] S. Ramachandran *et al*, "Generation and propagation of radially polarized beams in optical fibers." *Opt. Lett.* 34 (2009) 2525-7.
[2] P. Gregg *et al*, "Conservation of orbital angular momentum in air core optical fibers." arXiv: 1412.1397 (2014).
[3] C. Brunet *et al*, "Design, fabrication, and validation of an OAM fiber supporting 36 states." *Opt. Expr*. 22 26117 (2014).
[4] N. Bozinovic *et al*, "Terabit-scale orbital angular momentum mode division multiplexing in fibers." Science 340 (2013) 1545-8.
[5] G.C.G. Berkhout *et al*, "Efficient sorting of orbital angular momentum states of light." *Phys. Rev. Lett.* **105** 153601 (2010).
[6] J. Sun *et al*, "Generating and identifying optical orbital angular momentum with silicon photonic circuits." *Opt. Lett.* **39** (2014) 5977-5980.
[7] Y. Ren *et al*, "Adaptive optics compensation of multiple OAM beams prop. through emulated atmospheric turb." *Opt Lett* **39** (2014) 2845-8.
[8] J. Wang *et al*, "Terabit free-space data transmission employing orbital angular momentum multiplexing." *Nat. Photonics* 6 (2012) 488-96.
[9] N. Bozinovic *et al*, "Control of orbital angular momentum of light with optical fibers." *Opt. Lett.* 37 (2012) 2451-3.
[10] L. Marrucci *et al*, "Spin-to-orbital conversion of the angular momentum of light and its classical and quantum applications." *J. Opt.* **13** 064001 (2011).
[11] S. Slussarenko *et al*, "Tunable liquid crystal q-plates with arbitrary topological charge." *Opt. Expr.* **19** (2011) 4085-4090.