Ring-Core Fibers Supporting Propagation of OAM Modes

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Abstract *Ring core fibers are particularly well-suited for spatial division multiplexing, by permitting good separation of mode effective indices. In the case of orbital angular momentum modes, the weakly guiding mode can be violated to greatly increase the number of supported modes.*

Introduction

The design of fibers to support spatial division multiplexing (SDM) must be informed by clear objectives at the system level. The many varieties of fibers enabling SDM - multicore fiber, few mode fiber for LP (linearly polarized) modes or orbital angular momentum (OAM) modes - have distinct characteristics that can be adapted to different requirements. All SDM solutions seek to increase the throughput of a single fiber, but they must also deliver reduced cost per bit. Adoption of SDM will require clear advantages over fiber bundling. That advantage can come via increased energy efficiency in the face of the encroaching nonlinear Shannon limit[1], or it may come via efficient optical amplification strategies[2], or it may hinge on enhanced information density[3]. These system level concerns must be translated into fiber design targets. In this paper, we will look specifically at the exploitation of OAM modes.

Weakly vs. Strongly Guiding

A fiber is considered weakly guiding when the cladding and guiding region have refractive indices that are roughly equal. That is, when the index contrast

$$\Delta n = \frac{n_{guided}^2 - n_{cladding}^2}{2n_{guided}^2}$$

is much less than 1%, as in typical single mode fiber. For fibers supporting several modes, a small index contrast leads to LP modes which solve the scalar version of Maxwell's equations. These modes can be used for mode multiplexing, although they typically experience significant mode mixing.

Orbital angular momentum modes have a helical phase front[4] that rotates about the axis of propagation; the amount of phase rotation defines the OAM order. To support OAM modes in a fiber, we require eigenmodes that are separated sufficiently in effective refractive index to avoid degeneracy into LP modes. In other words, we seek a fiber design that results in true vector modes rather than the scalar solutions. This can be accomplished by violating the weakly guiding condition and moving to high index contrast fiber.

Orbital angular momentum modes are constructed from degenerate eigenmodes that differ only in their even and odd symmetries. They are combined with a $\pi/2$ phase difference to produce the helical wavefront. As their constituent eigenmodes have identical effective refractive indices and propagation constants, they are much less prone to interaction than LP modes. The opposite topological charges of OAM modes thwart modal interaction, especially for higher-order modes[5]. While LP modes have typically required the use of receiver side digital signal processing (DSP) to undo modal mixing and recover transmitted data[6], OAM modes have been demonstrated to withstand modal mixing for distances to 1 km[7] with no special DSP to recover data.

Many fiber characteristics are determined by the choice of index contrast. It will affect the level of attenuation (greater index contrast tends to higher attenuation) and the number of supported modes. It will affect its manufacturability and durability (greater index contrast makes fiber more brittle). The index contrast also is the playing field where we can attempt to space out our modes to avoid interactions. The more modes we wish to support while avoiding modal mixing, the higher index contrast we will require.

Application Scenarios

In considering the many application scenarios for spatial multiplexing, OAM offers advantages for low complexity transceivers. The mixing of LP modes requires multiple input multiple output (MIMO) processing whose complexity scales with the square of the number of modes. OAM modes that do not mix have complexity that scales linearly with the number of modes. For links with significant accumulated chromatic dispersion and limited signal to noise ratio, the DSP to compensate dispersion and for forward error correction may be significant and dominate receiver complexity vis-à-vis MIMO. However, in applications

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that are short reach the MIMO processing could dominate receiver complexity.

OAM fibers with low modal interactions lead to low crosstalk across data channels. However, fiber imperfections accumulate with transmission distance, causing crosstalk to grow. A demonstration of OAM fiber transmission at 100 km[8] led to modal mixing that required 4x4 MIMO to recover data from 4 channels, even then 8 channels were propagated. While MIMO free propagation was not possible as in the 1 km case, the MIMO complexity required only 16 filters rather than 64 filters, a significant savings in complexity compared to typical LP multiplexing.

While SDM is still in its infancy, it could complement wavelength division multiplexing (WDM). For instance, links tolerating greater complexity could seek to maximize capacity by supporting a great number of wavelengths and modes, perhaps even in multiple cores. For scenarios with tighter cost constraints, SDM could offer another degree of freedom, another trade-off to allow system designers to find a Goldilocks solution with just enough SDM and WDM.

Data centers and high-performance computing would appear to be good choices for OAM exploitation. While SDM requires specialty fiber, this is not an issue with data centers that are deployed and/or updated with some frequency. The information density of spatially multiplexed systems is very high and can be used to reduce the excessive number of fibers in data centers. Both latency and cost pressures preclude the use of forward error correction and other DSP. Distances are short enough to keep crosstalk very low in OAM systems and avoid MIMO complexity in transceiver DSP.

High Capacity OAM Fibers

Having established the importance of avoiding modal mixing in fibers supporting OAM, we can now examine how we can go about designing fibers to achieve high capacity. Ring core fibers (RCF) have an index refraction profile matching the donut shaped intensity profile of OAM modes to facilitate coupling of light in and out of the fiber. We have developed design tools for RCF[9] and have used them to design several fibers to support OAM[10-12] with capacity ranging from 4 to 36 information channels.

A frequent figure of merit used for the OAM fiber design is the effective index of refraction separation between neighboring (in terms of effective refraction index) modes. Modes separated by at least 10^{-4} are expected to have tolerable crosstalk for data communications. This metric is strictly ad hoc and based on early OAM experimental demonstrations[13]. Achieving both high capacity (supporting many modes) and good index separation requires that the index contrast be high. The difference in the cladding and guiding region indices of refraction are an upper bound on mode separation. A greater difference leaves room for more modes with the potential for low crosstalk.

We demonstrated the fiber supporting the greatest number of OAM modes[10], able to guide modes up to OAM9 and OAM-9 (up to 9 rotations of 2π rotating right and left, respectively). Given polarization multiplexing, for OAM that is right circular and left circular, a total of 36 information channels could be supported. We were able to achieve this record number of modes by maximizing the index contrast in the fiber. The center of the fiber was hollow, for an index of refraction of one at the central region of the fiber. The guiding region was annular and very thin relative to its diameter. The light travels in the thin glass ring core and not in the hollow air “core” at the center.

Consider the fiber profiles illustrated in Fig. 1. We have chosen four fiber designs that illustrate the impact of parameter choices. In the upper left we have the highest index contrast of 27% when using an air core, and in the lower left we have a reference single mode fiber (SMF) design for contrast. For SMF we have an index contrast of 0.37%, well within the weakly guiding approximation. High index contrast posed several challenges in fabrication, and led to high attenuation in the fiber. Transmission demonstrations were limited to a few meters, but served as a proof of

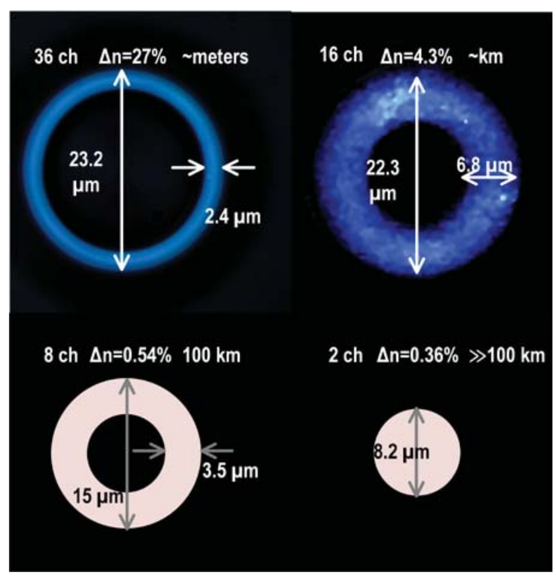

Fig. 1: Enhanced scanning electron microscope photos of upper left: air core RCF[10], upper right: thick core RCF with high contrast[12]; and cartoons of fibers in lower left: thick core RCF with low contrast[8], lower right: typical SMF with low contrast

concept for achievable mode density.

The next two example designs form a middle ground. When using a low index contrast fiber, 0.54%, transmissions of 100 km were achieved[8] with attenuation of only 0.2 dB/km. The low contrast limited the supported modes to orders |2| and |3|. They used a refractive index notch to achieve effective refractive index separation of 2.5e-3 between orders |2| and |3|, but required 4×4 MIMO at the receiver to separate data transmissions on each mode group.

We used a particle swarm optimization technique for step index fiber to contrast the performance of two significant parameters: the thickness of the ring and the level of index contrast[12]. We learned that the extreme index contrast of an air core fiber was not necessary to achieve our targets of 12 or 16 information channels. Our air core fiber was able to offer good separation of all supported modes, but lower contrast was sufficient to separate a large subset of modes. Given the greater complexity in fabrication and susceptibility to attenuation, lower capacity can be traded off for a more robust fiber.

We found that thick and thin RCF fiber designs offered similar capacity in terms of supported modes, however, their system choices were quite distinct. Thin rings supported no parasitic modes (ones with double intensity rings deemed difficult to couple), however they were prone to fabrication errors due to their exacting thinness. The thick ring fibers are easier to fabricate, but support parasitic modes vulnerable to siphoning off energy from targeted modes.

The thin ring fiber was originally favored as it favored OAM modes with a single intensity ring. However, thick core fibers have a greater optimization space for finding supported modes. We explored this space with particle swarm optimization, using the analytical equations we developed for fiber cutoff in RCF[9]. These equations allowed us to only explore achievable fiber design regions identified a priori.

Modeling modal interactions

We designed our fibers using the ad hoc criteria of minimal effective refraction index separation for adjacent modes. However, we also need to examine how this separation will deteriorate as we propagate in a physical fiber. For this we require numerical models that predict coupling as the fiber exhibits imperfections in its geometry (an elliptical profile instead of circular) or birefringence. We can adapt techniques developed to model mode coupling in multimode fibers[14, 15] and apply them to OAM fibers.

We used perturbative analysis[16] to examine the extreme index contrast, thin RCF[10] for fiber imperfections. We focused on the OAM mode purity that leads to dominant and secondary components that can cause degeneracy. This purity effect was ignored in the design of the air core fiber, but adopted in the particle swarm objective function[12] for later designs. We used Monte Carlo simulations of random fiber rotations to uncover coupling mechanisms and their impact on bit error rate performance.

We extended the perturbative approach to incorporate a mode-solver based model[17] for coupling that provided more realistic effects under elliptical deformation. Unlike other approaches, we were able to predict the greater perturbation robustness of higher order modes which had been observed experimentally.

Multiplexers

Before OAM fibers can be fully exploited and adopted for commercial systems we need multiplexers that can maintain modal separation. When using MIMO processing at the receiver, we can permit multiplexing and demultiplexing to mix data on different modes. However, for OAM that strives to keep processing low, this behavior is unacceptable.

Experimental demonstrations rely exclusively on free space multiplexers[13, 10, 7, 8], using fixed q-plates and/or reprogrammable spatial light modulators (SLMs). We developed the perfect vortex techniques[18] with SLMs to facilitate coupling into very thin core fibers; while flexible and effective it is too complex outside the research laboratory. We are working on integrated silicon photonic solutions[19] for lower cost and smaller size.

Conclusions

We have discussed the characteristics of spatial multiplexing with orbital angular momentum modes. These characteristics favor the targeting of short reach systems requiring simple transceivers and a high density of information, such as for data centers and high-performance computing. We reviewed several illustrative OAM fiber designs, and discussed fiber design tools and methodology. The designs can be probed by numerical models to predict practical degradations in nonideal fibers. While previous fiber designs focus only on capacity, fibers that are also robust to impairments would offer improved performance.

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