Decoupling and Asymmetric Coupling in a Triple-core Photonic Crystal Fiber (PCFs)

Y. Yan, J. Toulouse, I. Velchev, S. V. Rotkin
Lehigh University, 16 Memorial Dr. E., Bethlehem, PA 18105, U.S.A.
yay2@lehigh.edu, jt02@lehigh.edu

Abstract: We simulate and measure decoupling in triple-core PCFs. We obtain the three supermodes and calculate the coupling parameters. The measured parameters agree well with the calculated ones. The inter-core coupling is found to be asymmetric.

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1. Introduction
Multicore photonic crystal fibers have recently attracted substantial interest but, so far, most of the work has focused on dual-core PCFs. However, PCFs with three or more cores offer a much wider range of possible applications. In this paper, we report results on the inter-core coupling in a three-core fiber, which may provide a glimpse into these applications.

In the case of linear approximations, the coupled-mode equations for the triple-core PCF are:

\[
\begin{align*}
\frac{dA_1}{dz} &= i\kappa_1 A_1; \quad \frac{dA_2}{dz} = i\kappa_2 A_1 + i\kappa_1 A_2; \quad \frac{dA_3}{dz} = i\kappa_3 A_1 \\
\end{align*}
\]

where \(A_1, A_2\) and \(A_3\) are the amplitudes in cores 1, 2 and 3 at \(z\), \(\kappa_1\) and \(\kappa_2\) denote the coupling coefficients between core 1 and 2, and core 2 and 3 respectively. Solving the system of equations above yields the supermodes of the propagation:

\[
\tilde{A}_d = \begin{pmatrix} \kappa_1 \\ 0 \\ -\kappa_2 \end{pmatrix} A_1 \\
\tilde{A}_i = \begin{pmatrix} \kappa_1 \\ \sqrt{\kappa_1^2 + \kappa_2^2} \\ \sqrt{\kappa_1^2 + \kappa_2^2} \end{pmatrix} A_1 e^{i\sqrt{\kappa_1^2 + \kappa_2^2}z} \\
\tilde{A}_s = \begin{pmatrix} -\kappa_1 \\ \sqrt{\kappa_1^2 + \kappa_2^2} \\ \sqrt{\kappa_1^2 + \kappa_2^2} \end{pmatrix} A_1 e^{-i\sqrt{\kappa_1^2 + \kappa_2^2}z} \\
\]

The optical amplitude distribution among the three cores is then a superposition of these three modes. At \(z = 0\), the amplitude distributions corresponding to the three supermodes are shown in Fig 2, where \(\kappa_1\) and \(\kappa_2\) are set equal for illustration purposes only.

![Fig 1 The fiber geometry: cores are marked by circles, the air hole diameter is \(d=1.08\mu m\), the pitch is \(\Lambda=2.52\mu m\) and the core spacing is \(3\Lambda\).

For the decoupling mode \(\tilde{A}_d\), the amplitudes in the three cores do not change with distance, and no light is found in the central core, as shown in the first graph in Fig 2. In all three cases, by definition, light launched according to one of these supermodes will propagate with a constant ratio of the amplitudes in the three cores.

2. Simulation
We have developed an efficient and versatile numerical code to simulate the propagating wave fields [1]. We first modeled two anti-phased beams incident into the two side cores, as in the decoupling mode \(\tilde{A}_d\). The results are shown in Fig 3. After 10cm, the intensity distribution indeed remains unchanged. We compare this with the...
result obtained for an in-phase beam under the same launching conditions. After 10cm, we see that 59% of the energy initially in the side cores has been transferred to the central core.

In the second simulation, we modeled the propagation of light launched into the central core. The first complete energy transfer from the central core to the two side cores is found at \( z = 63.7 \text{cm} \), which is the coupling length.

3. Experiments
We have experimentally investigated the inter-core coupling by launching light \( \lambda = 632.8 \text{nm} \) into one single core. The output intensity distributions for launching light successively into the three cores are shown in Fig 5.

Comparison of these intensity distributions reveals some asymmetry in the inter-core coupling, most clearly seen in (a) and (c): no beam was found in core 3 in (a); while in (c), the light was transferred into core 1. This asymmetric intensity distribution indicates that the coupling coefficients \( \kappa_1 \) and \( \kappa_2 \) are not equal.

Launching light into the central core and measuring the intensities in the three cores at the output, we were able to determine the coupling coefficients and the corresponding coupling length from the propagation equations:

\[
\kappa_1 = 1.8833 \text{ m}^{-1}, \quad \kappa_2 = 2.1778 \text{ m}^{-1}, \quad L = \frac{\pi}{2\sqrt{\kappa_1^2 + \kappa_2^2}} = 54.56 \text{cm}.
\]

The values found from our experiments are in reasonable agreement with those obtained from our simulations, considering errors due to the discretization loss through computation; as well as with values obtained from an empirical formula used for couplers \([2]: x = 2.8903 \text{ m}^{-1} \) (for \( NA = 0.20 \)) and \( x = 1.5348 \text{ m}^{-1} \) (for \( NA = 0.21 \)), while the \( NA \) of our fiber is measured to be around 0.20. Further confirmation of the agreement between modelling and experiments was obtained by launching light into core 3. Using the propagation equations, our simulation predicted the intensity in core 3 to be 73.22% of the total, and the experiment yielded 72.49%.

4. Conclusion
We identified the supermodes in the triple-core PCF. The coupling coefficients and the coupling length were experimentally estimated and found to be in good agreement with simulations. We also observed an asymmetry in the coupling, which is possibly due to slight variation in the fiber parameters along its length.

5. References