Analysis of the Transmission Characteristics of the Central Core in a Seven-Core Optical Fiber Based on Silica Glass

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Abstract. *The transmission characteristics of the central core in seven-core fiber (7CF) are investigated both theoretically and experimentally. The 7CF is placed between two standard single-mode fibers (SMF), which forms a so-called S7S structure (SMF–7CF–SMF). From the simulation results it was found that the transmitted power through a S7S structure is highly sensitive to the wavelength of operation. The simulation results are supported by experimental measurements using three different measurement set-ups on spliced S7S structures. The transmission characteristics of the central core in the S7S structure were measured using an unpolarized broadband light source, unpolarized light from an erbium-doped fiber amplifier and polarized light from a tunable laser source. The results from this paper will be useful in the design of novel optical filters using S7S structures.*

Keywords*: optical fiber devices, multi-core optical fiber, wavelength filter.*

1 Introduction

Multi-core fibers (MCFs) are optical fibers that integrate more than one guiding core inside a single cladding. The number of cores can be arranged in a variety of patterns depending on their applications. Although the idea of including several cores in one cladding emerged in 1979 [1], it was not implemented for a long time because intensive research efforts focused on improving the properties of single-core fibers, extending the spectral range of the channels, increasing the capacity with wavelength-division multiplexing and raising the channel data rate. In 2010 MCFs were studied again for space-division multiplexing when reports predicted a capacity crunch in the near future because of the capacity limit of the current optical communication systems due to the limitations of amplifier bandwidth, nonlinear noise, and fiber fuse phenomenon [2].

MCFs can be divided into two groups based on whether the cores are coupled with each other or not, i.e., weakly coupled and strongly coupled. Each core of a weakly coupled MCF or uncoupled MCF (UMCF) is used as an individual spatial channel with a sufficiently low crosstalk between the neighboring cores (preferably lower than -25 dB or -30 dB) [3], [4]. To fulfill this requirement the coupling coefficient κ between the neighboring cores should be lower than 10^{-2} m^{-1} [5]. The other group consists of strongly or moderately coupled MCFs (CMCF), in which a decreased spacing between the cores intentionally induces coupling. For CMCFs the light propagates through multiple cores as a supermode and every supermode can be considered as one spatial channel [6]. In CMCF the coupling coefficient κ between the neighboring cores is larger than 10^{-1} m^{-1} [7]. The number and characteristics of the supermodes depend on the number of cores, their size, placement, index profiles, and pitch.

In MCFs the presence of a core near another core can be considered as a perturbation. The power is coupled from one core to another within the same cladding because each mode has an evanescent part, which is traveling in the cladding. This evanescent part experiences a perturbation by the other cores inside the multi-core fiber. Due to this coupling the energy passes back and forth between the cores along the length of the fiber. This coupling between the cores exhibits a sinusoidal spectral response, which is useful for constructing devices such as spectral filters, switches, splitters and couplers.

In this paper we analyze and study the transmission of a device consisting of two identical single-mode fibers that are axially spliced at both ends of a short length of seven-core fiber (SMF-7CF-SMF), as shown in Fig. 1. This structure is similar to S7S structures (SMF-MMF-SMF), but the multi-mode fiber (MMF) section has been replaced by a seven-core fiber (7CF) because in a 7CF one can vary the size, placement, index profiles, and pitch of the cores, in order to achieve the desired supermodes. This allows for much greater control over the coupling from an excitation fiber to the 7CF, as well as control over which supermodes and how many supermodes propagate along the SCF, as will be shown in the following section.

It is observed that the transmitted power in the 7CF becomes highly sensitive to the wavelength of operation and the length of this fiber because the power will be distributed throughout multiple supermodes, which will interfere throughout the propagation down the fiber. Then the power that is coupled and transmitted in the second single-mode fiber will be highly dependent on the distribution of light in the cores of the 7CF section. Due to the wavelength dependency of the interference, the transmission spectrum will have a periodic modulation. This modulation should be useful in the design of efficient fiber optic sensors [8-10] and novel spectral filters [11], [12].

This paper is organized as follows. Section 2 demonstrates the transmission properties of the light in the S7S fiber structure, assuming that the central core of the 7CF and the single-mode fibers are axially aligned at each splice. Section 3 introduces three different experimental set-ups with different light sources to measure the transmission probe spectra and a comparison between the simulation and the experiment for S7S devices using all set-ups. In section 4 the conclusions are presented.

2 SMF-7CF-SMF

We consider a S7S structure consisting of two identical single-mode fibers spliced (axially aligned) at both ends of a 7CF with length L, as shown in Fig. 1. The central core of the 7CF is excited by the fundamental mode of the single-mode fiber input. In this case, only supermodes that are circularly symmetric with nonzero intensity in the central core will be excited. Then, after a distance z, the power is transferred from the central core to the other cores and the optical field oscillates between a state where all the power is in the central core (the initial state at z=0) and a state where one-seventh of the power is distributed between the outer cores and the central core.

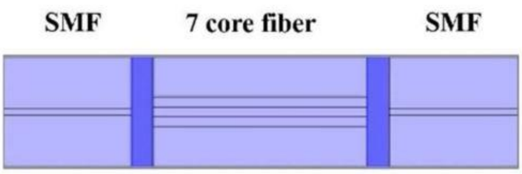

Figure 1. Diagram of the S7S device structure.

In the 7CF section each supermode has a different propagation constant. A phase difference Δφ develops between them as they propagate down the 7CF

$$\Delta\varphi = (\Delta\beta)L \quad (1)$$

where $(\Delta\beta)$ is the difference between the propagation constants of the two excited supermodes in the 7CF and L is the length of the 7CF. Analytical expressions have been developed describing the wavelength dependence of the propagation constants for supermodes inside the 7CFs with circularly distributed cores [13-15]. In addition, a semi-analytical model [16] calculated the transmission properties of light in the S7S using the equation

$$T(\lambda) = 1 - P_1 P_6 sin^2(2\sqrt{7}\, C(\lambda)L) \quad (2)$$

where P_1 and P_6 are the fractions of light carried by the two excited supermodes SM_1 and SM_6, respectively, C is the core-coupling coefficient and L is the 7CF segment length. The supermodes SM_1 and SM_6 that are circularly symmetric with the intensity in the central core will be excited, as shown in Fig. 2.

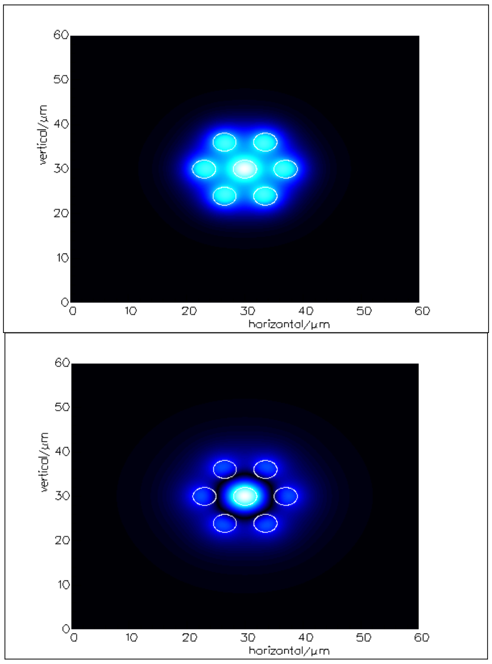

Figure 2. Electric field of the supermodes SM_1 and SM_6 calculated using a finite-element mode solver.

3 Experiment and results

The performance of the S7S structure in different wavelength ranges has been studied experimentally and through simulation. The S7S is prepared by splicing a 30-cm-long section of the fabricated 7CF [17] between two SMFs. The splicing was performed using the Fujikura FSM-45PM fusion splicer. This splicer has a profile alignment system for core-to-core alignment and many additional functions, which enable the splicing of dissimilar fibers. Three different experimental set-ups with different light sources are used to measure the transmission probe spectra. For each set-up the calibration for the used light source was made before the transmission characteristics of the S7S structure are measured.

3.1 Measurement with broadband light source

The first measurement set-up (Fig. 3) consists of a broadband light source and an optical spectrum analyzer (ANDO AQ6317). The broadband light source produces unpolarized light, which is a mixture of all possible polarization orientations. Such unpolarised broadband light is launched to the S7S structure. The optical spectrum analyzer is swept from 1400 nm to 1600 nm. The transmitted power spectrum of the S7S structure is recorded and a comparison between the simulation and the experiment for the S7S devices is made (Fig 4). We can see a slight wavelength offset between the experimental results and the simulations. We assume that this offset is due to the inaccurate length of the S7S structure and the power loss at the splice between the single-mode fiber and the 7CF.

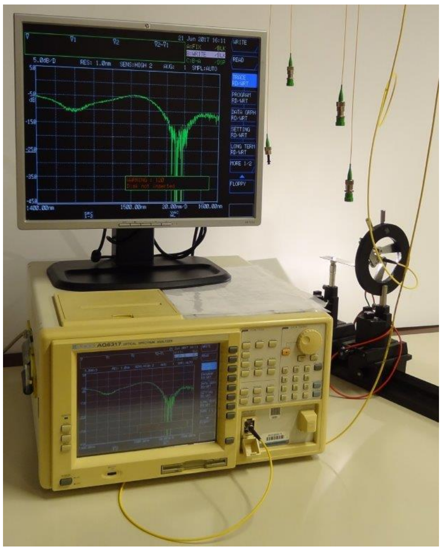

Figure 3. Transmission characteristics measurement set-up based on broadband light source and optical spectrum analyzer.

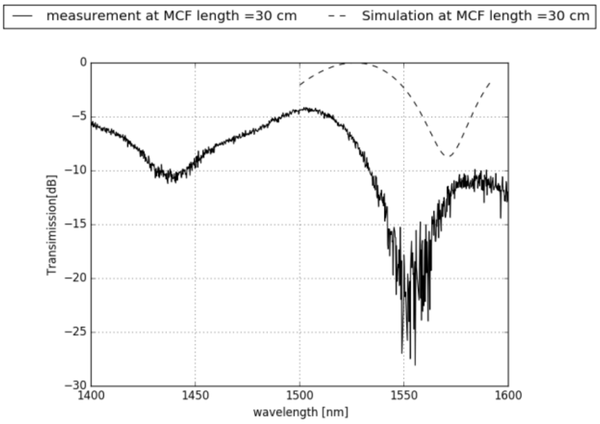

Figure 4. Comparison of simulated and measured transmission spectra of S7S devices using the broadband light source set-up.

3.2 Measurement with EDFA

The second measurement set-up consists of an erbium-doped fiber amplifier (EDFA) with maximum gain in the wavelength region 1510 nm to 1580 nm and an optical spectrum analyzer (ANDO AQ6317), as shown in Fig. 5. The light from the EDFA is also unpolarised. The light was launched to the S7S structure using the EDFA and the transmitted power spectrum was recorded using an optical spectrum analyzer. Fig. 6 shows the transmission spectra comparison between the simulation and the experiment for the S7S devices.

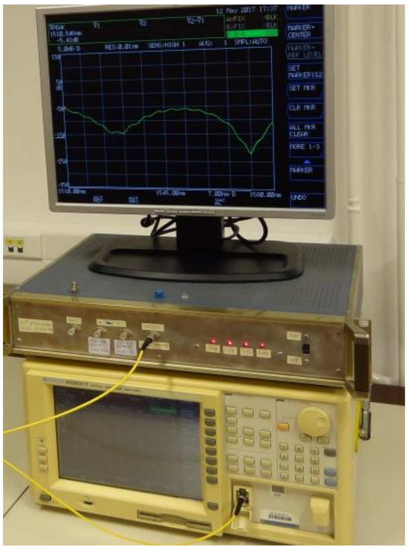

Figure 5. Transmission characteristics measurement set-up based on EDFA and optical spectrum analyzer.

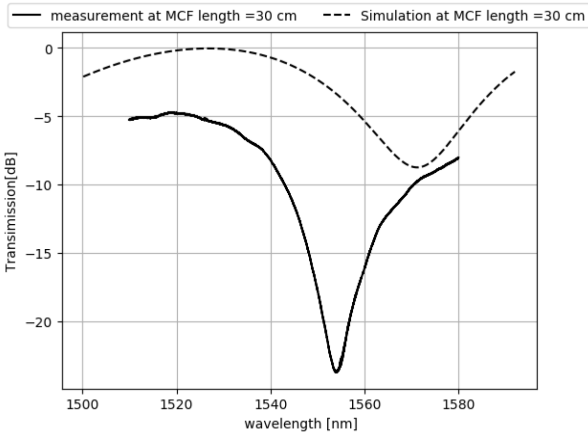

Figure 6. Comparison of simulated and measured transmission spectra of S7S devices using EDFA.

3.3 Measurement with tunable laser source

The third measurement set-up consists of a tunable laser source (HP 8167B), a polarization controller and an optical power meter. The tunable light source works at wavelengths from 1446 nm to 1592 nm and gives polarized light at its output. Light from a tunable laser source is launched to the S7S structure using the fiber polarization controller. The transmitted power spectrum was detected using an optical power meter, as shown in Fig. 7. The tunable laser source and power meter are integrated into a fully automated test environment for precise, fast and repeatable testing of the transmission characteristics of the S7S structure. Fig. 8 shows the measured transmission spectra and simulation results for the S7S devices. By tuning the fiber polarization controller's state different measurements of the transmission characteristics were made. A slight modulation in the transmission characteristics was noticed due to different polarization states.

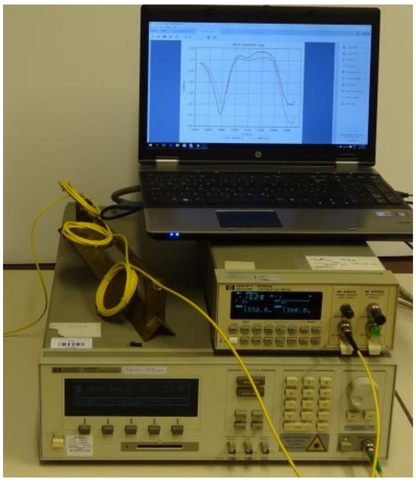

Figure 7. Transmission characteristic measurement set-up based on tunable laser source and optical power meter.

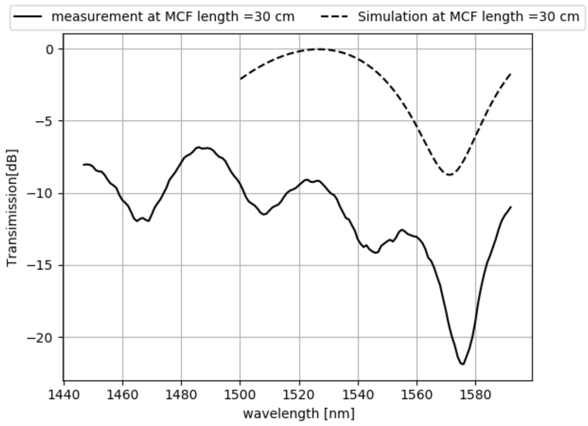

Figure 8. Comparison of simulated and measured transmission spectra of S7S devices using tunable light source.

4 Conclusions

Core-to-core coupling for wavelength filtering is introduced by comparing the experimental results and the numerical simulation of the S7S structure with a 30-cm-long section of the 7CF. The results show that the transmission modulation period is dependent on the wavelength.

The small differences between the simulation and the experimental results are due to the loss of the splicing between the SMF and MCF in the S7S device, errors in measuring the fiber geometry and the refractive index of the drawn fiber. Since the agreement between theoretical and experimental results are not excellent, this will be analyzed in our further work.

From measurements with a polarized tunable light source we noticed a small polarization dependency of the S7S structure. The polarized light produces modulation in the transmission characteristics. In future work this polarization dependency will be examined.

Acknowledgment

Delo je nastalo v okviru projekta »Sklopniki za mikrostrukturirana optična vlakna« (šifra projekta 25-11-4), ki se izvaja v sklopu operativnega programa za izvajanje evropske kohezijske politike v obdobju 2014-2020 kot neposredna potrditev operacije "Odprt, odziven in kakovosten sistem visokega šolstva - Projektno delo z gospodarstvom in negospodarstvom v lokalnem in regionalnem okolju - Po kreativni poti do znanja 2016-2020". Projekt sofinancirata Republika Slovenija in Evropska unija iz Evropskega socialnega sklada.

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