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Nonlinear Optical Fiber Couplers Made of Chalcogenide Glass

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Abstract. We demonstrate chalcogenide optical fiber couplers designed with a transmission spectrum response that varies with input power. The measured critical power is as low as 126 W at a wavelength of 1938 nm.

1 Introduction

Optical fiber couplers (OFCs) are typically four-port devices routinely used to divide or combine light in fiber optics devices and systems [1]. They generally operate in a linear regime, where the coupling ratio in between two output ports is independent of the power delivered to an input port. However, some OFCs can enter a nonlinear regime where the coupling ratio is a function of input power. Nonlinear OFCs are of particular interest because of their applications in all-optical switching and mode-locked fiber lasers. Initially proposed by Jensen [2], nonlinear OFCs have since been demonstrated experimentally in dual-core silica fibers, with a minimum reported critical power $P_c = 32\ kW$ at a wavelength of 620 nm in a 0.5 cm long fused-quartz dual-core fiber directional coupler [3]. Reported nonlinear OFCs are limited to critical powers in the order of tens of kW in response to the relatively low nonlinear refractive index of silica. In contrast, chalcogenide glasses are excellent candidates to make nonlinear OFCs with low P_c, thanks to their exceptionally high nonlinear refractive index that is ~3 orders of magnitude beyond that of silica. So far, chalcogenide OFCs have been demonstrated in the linear regime [5–9] including the first single-mode chalcogenide OFC [7] as well as chalcogenide OFCs such as power dividers, wavelength division multiplexers, and polarization beamsplitters [8]. To ensure a nonlinear response, the OFC design must ensure that the coupling length and nonlinear length are roughly equal [2].

Here, we present the first chalcogenide OFCs with a nonlinear coupling response. Two nonlinear OFCs made of As_2Se_3 are presented, showing a critical power as low as $P_c = 126\ W$, the lowest ever reported for any OFC. These OFCs will find applications for all-optical switching as well as act as saturable absorbers in mode-locked and Q-switch fiber lasers with low power threshold.

2 Experiment and Results

The output power of a nonlinear OFC is given by [2]: $P_{Through}(L) = \frac{P_0}{2}\left[1 + cn\left(\pi L/L_c|(P_0/P_c)^2\right)\right]$, and $P_{Cross}(L) = P_0 - P_1(L)$, where $P_{Through}$ is the output power on the same fiber where the input power is applied, P_{Cross} is the output power crossing to the coupled fiber, P_0 is the input power, L is the length of the coupling region, L_c is the length required for a complete power transfer from one fiber to the next, $cn(x|m)$ is a Jacobi elliptic function with argument x and modulus m. $P_c = \frac{2\pi}{\gamma L_c}$ is the critical power, where for $P_0 = P_c$ the power of through and cross output ports reach the same level, and γ is the waveguide nonlinearity. A practical nonlinear OFC requires a P_c that has access to low values and thus, its geometry needs to be designed in a way that provides both large γ and large L_c, while L_c should remain in the order of the nonlinear length. Nonlinear length, $L_{nl} = 1/P_0\gamma$, is the effective propagation distance at which the nonlinear phase shift is 1 rad.

The designed OFCs are prepared from two identical pieces of As_2Se_3 fiber with a core/cladding diameter of $20/240\ \mu m$ and a numerical aperture of 0.2 pretapered down to a cladding diameter of 144 μm. They are cleaved, polished, and coupled to SMF-28 using UV-cured epoxy. The fibers are subsequently set side by side in close contact on a tapering setup. Both fibers are heated to their softening temperature and stretched into tapered OFCs [10]. Figure 1 shows a schematic of the tapering setup. The degree of fusion between both fibers is chosen in a way that leads to a polarization independent OFC by controlling the temperature and speed of stretching [8]. The tapering process is interrupted when the fiber cladding diameter at the waist of the OFC reaches the desired final diameter.

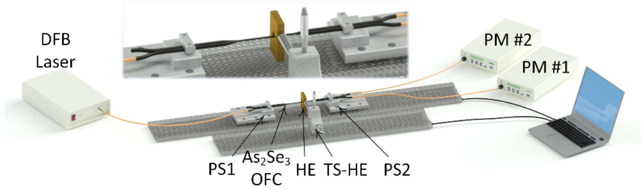

Figure 1. Schematic of the tapering setup. PS: pulling stage; HE: heating element; TS-HE: translation stage of the heating element; PM: power meter.

Two nonlinear chalcogenide OFCs with different coupling ratios are demonstrated. The first OFC (OFC #1) is fabricated with a waist length of $L = 3\ cm$ and a fiber cladding diameter of $6\,\mu m$ per fiber in the waist region. Figure 2 shows the transmission spectra of the through and cross ports of OFC #1. Although the OFC is fabricated with an adiabatic transition profile, it is slightly multimode because fibers are multi-mode, leading to transmission spectra that are wavelength dependent. To investigate the nonlinear behaviour of the OFC, pulses with different peak powers are sent into the OFC while both through- and cross-port outputs are monitored. Figure 3 shows a schematic of the characterization setup. Pulses injected to the OFC have a full width at half maximum of 1.4 ps

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and a repetition rate of 30 MHz at a central wavelength of 1938 nm. The overall length of SMF-28 from the amplifier output to the OFC input is 1.6 m. With a maximum peak power of 200 W in silica, the maximum nonlinear phase-shift prior to entering the OFC is thus negligible with 0.25 rad.

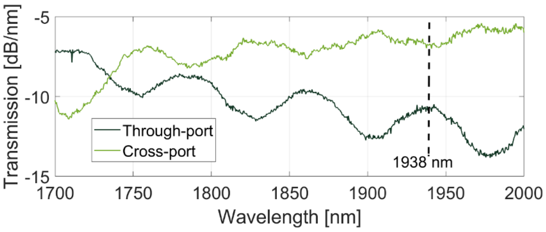

Figure 2. Transmission spectra of OFC #1.

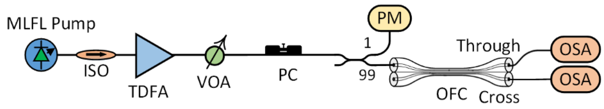

Figure 3. Schematic of the characterization setup.

Figure 4a shows the output power of OFC # 1 as a function of input peak power. In a linear regime, the coupling length of this OFC is $L_c \approx 1.6\,L$. While at low input power most of the power comes out of the cross-port, an increase of input power leads to an increasing fraction of power at the through-port. No evidence of saturation or nonlinear absorption is observed from the total power emerging from both ports. The linear behaviour is identified by straight asymptotes in fig. 4a. Figure 4b shows the relative output power as a function of input peak power. At low input power, more than 70% of the output power is in cross-port. This value drops down as the input power increases. At an input peak power of ~ 140 W, through and cross ports provide the same output power. Further increase of the input power makes through-port the dominant output port. At an input peak power of ~ 200 W, again the coupling ratio is 70:30 but this time 70% of the output power appears in through-port. Full lines are theoretical fits following with $P_c = 126\,W$ and $L_c = 1.6\,L$.

Besides the change in the coupling ratio, pulses propagating in the OFC experience spectral broadening due to self-phase modulation and temporal changes in the pulse shape. Over a length of L_c, the tails of the input pulses mostly couple to the cross-port while the middle part with a higher power level mostly stay in the through-port. Figure 5 shows the cross-port optical spectra for input pulses with different peak powers along with the numerical fit derived from the coupled-mode equation for a symmetric coupler.

A second OFC with a waist length of $L = 3\ cm$ and a fiber waist diameter of 9 μm is also fabricated. With a larger waist diameter and thus a lower nonlinearity, a larger critical power is expected in comparison to OFC #1. Figure 6 shows the relative output power of OFC # 2. At low input power, the coupling ratio is 80:20 with 80% of the power emerging from the cross-port. Increasing the input power changes the coupling ratio toward equalizing power of the two output ports. A theoretical fit matches the experimental data with $P_c = 239\,W$ and $L_c = 1.4\,L$.

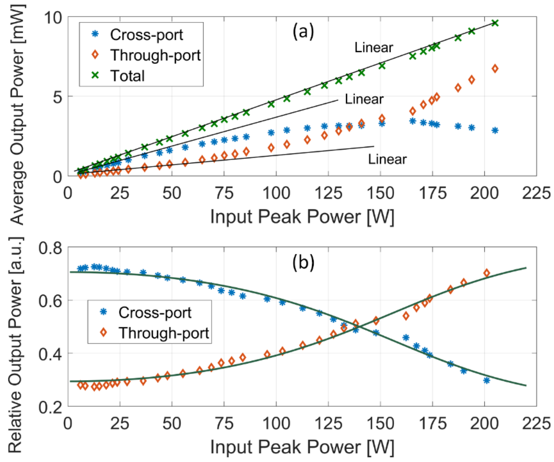

Figure 4. (a) Output power of OFC # 1 as a function of the input peak power. (b) Relative output power of OFC # 1.

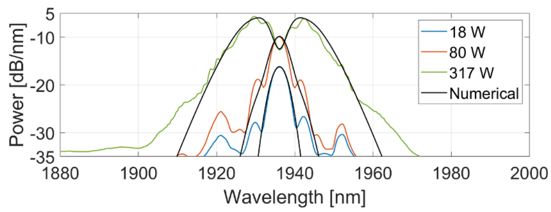

Figure 5. Cross-port optical spectra of OFC #1 for input pulses with different peak powers.

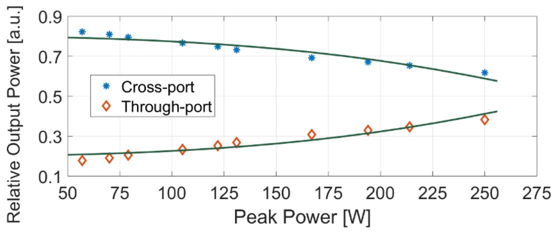

Figure 6. Relative output power of OFC # 2.

In conclusion, we have experimentally demonstrated the nonlinear behaviour of chalcogenide OFCs. These nonlinear OFCs show the excellent potential of nonlinear chalcogenide OFCs for applications such as all-optical switching and passively mode-locked lasers with low power threshold.

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