

High power all-fiber grating based multiplexers for 100 W class systems

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ABSTRACT

New space laser communications aim for Terabit per second (Tbps) capability (e.g. Hydron mission and ESA standardization group ESTOL). These multichannel systems will require hundreds of Watts on combined power for uplinks. This can be achieved by wavelength multiplexing of several amplifiers into a single mode output to a telescope. To achieve more compact, robust and lower loss multiplexing solutions than free space optics, we use Fiber Bragg Grating (FBG) rather than bulk gratings. As they are reflective filters, they are traditionally used with circulators to achieve wavelength multiplexing. However, these solutions are limited by the power handling of the circulators, which are, at best a few tens of watts for micro-optics components. The alternate approach is to use two FBGs in a fiber interferometer made with fused fiber couplers (FFC). FFC and FBG are widely used in high power fiber lasers and amplifiers because of their low excess loss and high-power handling. Two types of fiber interferometer were realised. A Michelson filter (MF), composed of a 50% FFC with 2 FBGs, one in each output fibers, and a fiber Mach-Zehnder Interferometer (MZI), composed of two couplers on parallel fibers, with FBG on each fiber between the couplers. With the proper phase adjustments, The MF is a transmission filter, and the MZI is a full wavelength multiplexer. The interferometers are stable because they are small and balanced. We show that isolation/back-reflection of 30 dB can be achieved with power handling of more than 50 W.

Keywords: High power, WDM, optical fiber, fiber interferometers, gratings, fiber Bragg gratings, all-fiber, wavelength multiplexers

1. INTRODUCTION

The new space telecommunications are requiring Terabit per second (Tbps) data transmission rates (e.g. Hydron mission and ESA standardization group ESTOL), leading to the need of high-power optical transmitters with a few 100 W output in Single Mode Fibers (SMF). The present performance of optical fiber amplifiers are around 100 W [1], thus, to achieve higher power, wavelength multiplexing of several amplifier outputs is necessary. All the currently proposed methods use free space part with prisms, gratings and mirrors, or multimode fibers to combine the beams from SMF into one output. We are developing all SMF multiplexers based on Fiber Bragg Gratings (FBGs)/Mach-Zehnder Interferometer (MZI), an all-fiber solution to reduce footprint and alignment requirements.

The combining of couplers or MZI with FBGs to create wavelengths filters and multiplexers has been proposed almost 40 years ago [2], but other technologies, such as thin film filters (TFF), have dominated the market as they are better suited for volume production. But TFF have a power limitation whereas fused fiber couplers and FBGs are widely used in high power fiber lasers and amplifiers because of their low excess loss. Couplers are spliced in single-mode fiber lasers with hundreds of watt outputs, while gratings are used in kW lasers. A FBG can be used as a wavelength multiplexer when spliced to a circulator, which is limited to the power rating around ten Watts. An all-fiber solution will circumvent this limitation. However, they come with their fabrication challenges. To obtain high isolation, high power handling and low back-reflection, the fused couplers reproducibly have a 50% coupling ratio within a few nm of the FBGs wavelength and low loss. And the two FBGs, written on different fibers must be equal distance from the coupler and their spectrum must be low loss, have a high reflectivity and overlap.

In this work, stable fused coupler based Michelson and Mach-Zehnder interferometers are built, addressing the fabrication challenges. A full Michelson filter is presented.

2. ALL FIBER INTERFEROMETERS

2.1 Balanced fiber interferometers

A fiber MZI is made by cascading two 50% fused couplers (Fig. 1: Compact all-fiber Mach-Zehnder interferometer). In order to make the interferometer mechanically stable, it is made by fusing two couplers separated by a 10 to 20 mm on two parallel fibers. As the two arms are the same length, the interferometer is inherently balanced and can be bonded on a single substrate and packaged like other fused couplers or combiners. The interferometer phase can be change temporarily by mechanical force or temperature, or permanently by UV or fs laser writing.

This compact approach makes the component stable. When matched FBGs are added after a 50% coupler, a Michelson interferometer is created, which can be used as a transmission filter (Fig. 2), or to transform a MZI into an optical add/drop multiplexer (OADM) (Fig. 3). Both these interferometers require phase adjustment to perform as a filter or multiplexer. For the Michelson filter, the phase is adjusted so that the wavelength reflected by the FBGs interfere constructively in the second input fiber. The signals outside the FBG passband are lost in the output fibers. For the MZI, the phase on the input side of the FBGs is adjusted in the same manner as for a Michelson filter. For all the other wavelengths, the phase is adjusted after the FBGs to compensate both the phase induced by the FBGs and the phase adjustment induced before the FBGs so that the 100% of other wavelengths go straight through the MZI. There are actually two possible phase adjustments that work for the MZI, one where the signal stays in the same fiber (odd π phase shift) or crosses to other fiber (even π phase shift).

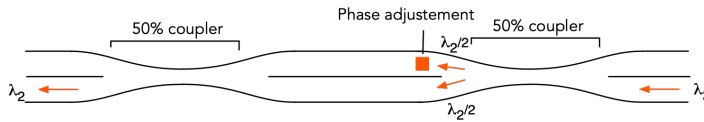


Fig. 1: Compact all-fiber Mach-Zehnder interferometer

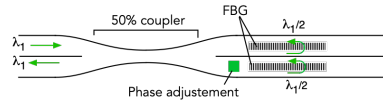


Fig. 2: Michelson filter

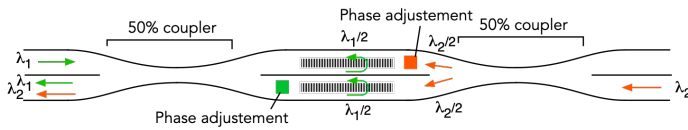


Fig. 3 : Mach-Zehnder/Bragg OADM

2.2 Fused fiber couplers

In order for these interferometers to have good performance such as low excess loss and high add/drop efficiency, the couplers must have a coupling ratio close to 50%. Couplers are made by fusing and pulling two fibers together. The pulling process is stopped, and the heat source removed when the desired coupling ratio is achieved. Unfortunately, the heat skews the measurement, and the coupling ratio is generally not perfectly achieved. Typical commercial tolerances are $\pm 1.5\%$ at

target wavelength. Because the MZI require two matched couplers to achieve good performance, we were able to reduce this tolerance to $\pm 0.25\%$, which translates into making the 50% coupling ratio within 2 nm of the target wavelength (Fig. 4). A compact MZI made of two of such couplers showed a 35 dB fringe contrast (Fig. 5). The phase was change by differentially heating the two arms of the MZI.

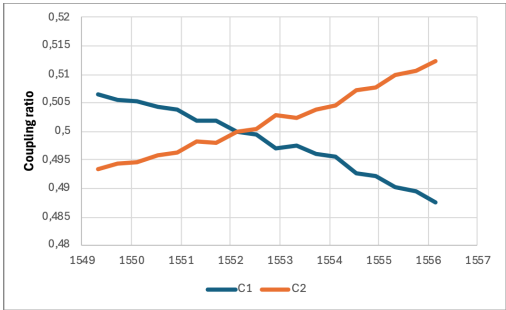


Fig. 4: Coupling ratio of a fused coupler made with target wavelength of 1552 nm for a 50% ratio

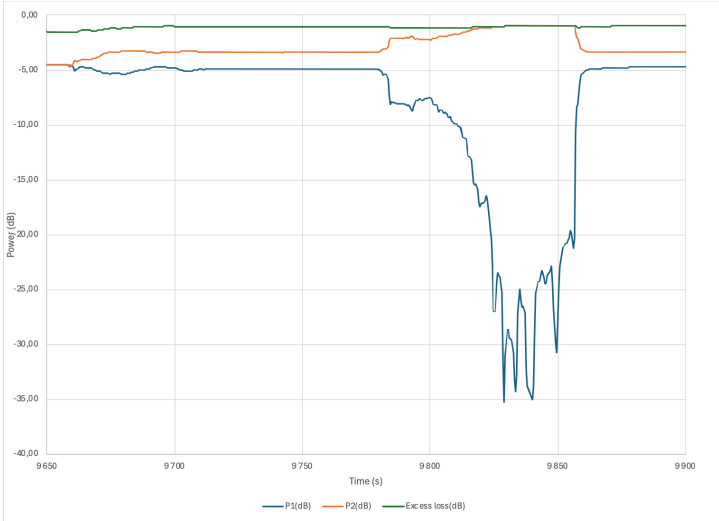


Fig. 5: Phase change of a MZI

2.3 High power handling

The other important aspect of the fused fiber technology for the high-power applications is the low excess loss. A coupler sample with an excess loss below 0.1 dB was observed with a thermal camera. The coupler was made for a Michelson filter and is bonded with optical UV epoxy on a slotted aluminum substrate. This opened substrate gives access to the laser beam for the writing of the FBGs. The substrate does not sit on a heat sink. The power was increased to 46 W and the results are shown in (Table 1). The total power of the two output fibers as well as the back reflection where measured. A thermal image is shown in Fig. 6. The hottest point recorded in the test was 66.4°C, corresponding to a 44°C increase at

46.6 W. However, it is important to note that the hot point is not on the coupler nor the output fiber exiting the substrate, but on the loose output fibers. This is because of the scattering or higher order mode coupling in the coupler. Power lost from the fundamental mode remains partially guided as cladding modes in the bare silica fiber, until it reaches the point where the fiber is bonded to the substrate. The temperature increase at the bonding point is less than 7 °C at maximum power. This provides a huge margin to increase the power if the output fibers are properly managed and heatsinked.

Table 1: Hottest spot temperature measurement vs input power (at 1565 nm)

Input power (W)	Total output power (W)	Back reflection (dB)	Hot point temp. (°C)	increase temp.(°C)	increase temp./W
4,88	4,66	-70,76	27	5	1,00
9,5	9,1	-70,86	33	11	1,10
14,3	13,5	-70,93	36	14	0,93
19,5	18,3	-70,71	40	18	0,90
24,4	22,6	-70,76	46	24	0,96
28,75	26,8	-70,79	47	25	0,83
32,2	30,8	-70,82	53	31	0,89
37,8	35,8	-70,71	52	30	0,75
42,2	39,6	-70,85	61	39	0,87
46,5	43,6	-70,86	66	43	0,86

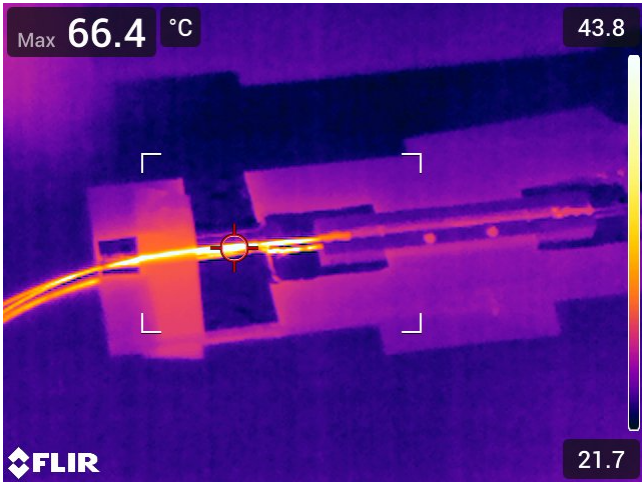


Fig. 6: Thermal image at high power

3. FIBER BRAGG GRATINGS

3.1 Writing strategy

Conventional UV phase-mask inscription in photosensitive fibers can produce nonuniform exposure, resulting in variations in the induced refractive index and, consequently, different grating responses. In contrast, point-by-point fs laser inscription provides a precise and flexible method for writing core-specific FBGs. The induced refractive index modification depends on the focal spot size and exposure conditions; by carefully controlling these parameters and

Commenté [SL1]: The other main problem is that hydrogen loading to get photosensitivity in low-loss standard fiber is not compatible with fiber flame-fusing.

compensating for aberrations [3] identical FBGs can be accurately inscribed once the core positions are properly identified. Although an all-fiber Michelson OADM has previously been demonstrated [4], its high coupler insertion loss limits its suitability for high-power applications. The Michelson OADM presented here therefore employs a low-loss coupler with an insertion loss below 0.5 dB. Another challenge in realizing a high-quality Michelson filter is the phase mismatch between its two arms. The fs laser inscription can also provide precise control of the relative optical phase through the inscription of low-loss waveguide structures within the fibers, thereby improving the filter response.

3.2 Inscription method

FBGs are inscribed using a fs laser with a pulse duration of 210 fs at a wavelength of 1030 nm and a repetition rate of 602.5 kHz. The beam is focused into the fiber core through a plano-convex aspheric lens (Newport, NA = 0.55) mounted on a two-dimensional (Y-Z) Aerotech air-bearing translation stage, while the fiber is mounted on a high-precision one-dimensional (X) Aerotech air-bearing translation stage. A plane-by-plane writing scheme is employed, with a set of cylindrical lenses used to shape the focal volume and produce planar refractive-index (RI) modifications. Because strong grating inscription requires precise alignment between the fiber core and the laser focal spot, the fiber trajectory is first mapped using a camera-based image-matching procedure. A reference image is acquired at the initial position after adjusting the focus and identifying the fiber center. The sample is then translated by 1 mm along the X-axis, and the Y-Z stages are adjusted until the newly acquired image matches the reference image. The corresponding X, Y, and Z coordinates are recorded, and this procedure is repeated along the entire fiber path. As shown in Fig. 7(a), the measured trajectories of the upper and lower branches are fitted with cubic polynomials, which are subsequently used to predict the transverse position of each branch during grating inscription. Fine localization of each core is then performed by identifying the focal-spot position that maximizes the grating coupling coefficient. Although this method has previously been demonstrated in single-core fibers [5], the present work extends it to mapping of multiple fibers with arbitrary curvature profiles. As shown schematically in Fig. 7(b), a series of weak, uniform FBGs are inscribed in each core at different transverse displacements around its initially estimated position. Their reflected signals are measured using an optical backscatter reflectometry (OBR) system, which spatially resolves the individual gratings along the fiber, as shown in Fig. 7(c). Because all probe gratings are written under identical exposure conditions, variations in their reflected signals primarily represent changes in the overlap between the laser focal volume and the guided-mode field. The signal varies approximately as a Gaussian function of transverse displacement, with its maximum identifying the core-center position [3], as illustrated in Fig. 7(d).

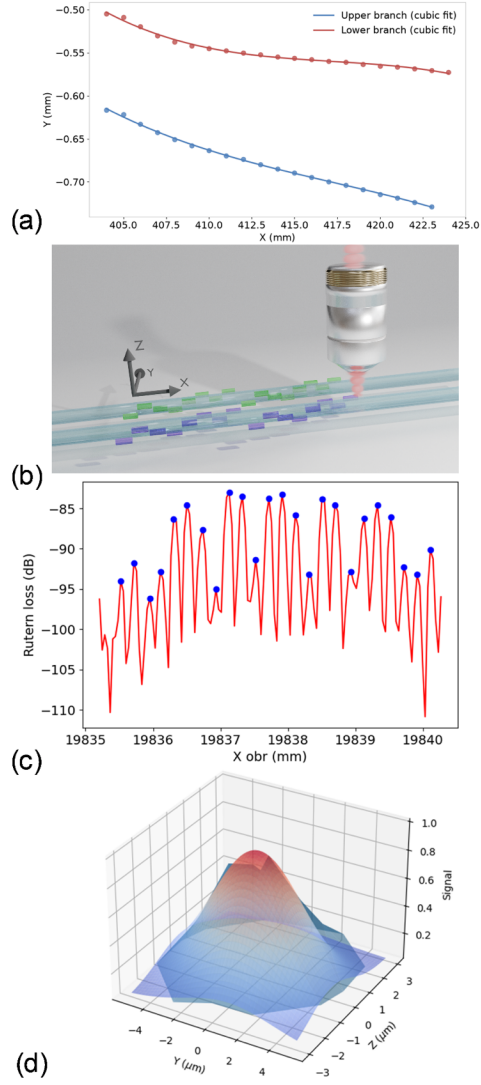


Fig. 1: (a) Camera-measured trajectories of the upper and lower fiber branches along the X -axis, together with their cubic polynomial fits. (b) Demonstration of the core positioning process in two branches. Green probes are written at upper branch and violet probes are written at lower branch. (c) The return loss from OBR. (d) Gaussian fit on OBR signal.

3.3 Experimental results

The repeatability of the fs laser inscription process was first evaluated by fabricating ten FBGs under identical exposure conditions. Fig. 8(a) presents the average reflection spectrum of the ten gratings, with the shaded region representing fluctuations around the standard deviation. The gratings exhibit similar spectral profiles and reflection strengths, while their central Bragg wavelengths remain within ± 0.108 nm of the mean value. These results demonstrate good inscription repeatability; however, the remaining wavelength variation can introduce spectral and phase mismatch between the two arms of the Michelson filter. A post-inscription trimming step was therefore investigated to provide finer control of the effective refractive index.

The trimming process was performed by applying a uniform, nonperiodic DC exposure over a 10 mm long section of the fiber. The induced Bragg wavelength shift, ($\Delta\lambda$), and the corresponding phase change, ($\Delta\phi$), were characterized as functions of the laser fluence and number of passes. As shown in Fig. 8(b), both parameters strongly influence the magnitude of the induced refractive index modification. At the lowest fluence of 2.14 J/cm², the wavelength shift remains negligible even after 15 passes. Increasing the fluence to 4.24 J/cm² produces a moderate shift of approximately 0.15 nm, although the response begins to saturate at higher pass numbers. At 4.91 J/cm², the wavelength shift increases progressively with the number of passes, reaching approximately 0.35 nm after 15 passes. This shift corresponds to a phase change exceeding 2π , providing a sufficient tuning range for compensating the relative phase mismatch between the two arms of the Michelson interferometer.

A further increase in fluence to 5.60 J/cm² produces a substantially larger wavelength shift, approaching 1 nm after 15 passes. However, this condition enters a high-loss modification regime and is therefore unsuitable for low-loss filter fabrication. The intermediate fluence regime, particularly 4.91 J/cm² with an adjustable number of passes, offers the best compromise between tuning range and induced loss. Under these conditions, the additional optical loss remains below 0.1 dB while providing sufficient phase control for optimizing the Michelson-filter response. Consequently, the required phase correction can be applied by selecting the appropriate number of passes at a fluence of 4.91 J/cm².

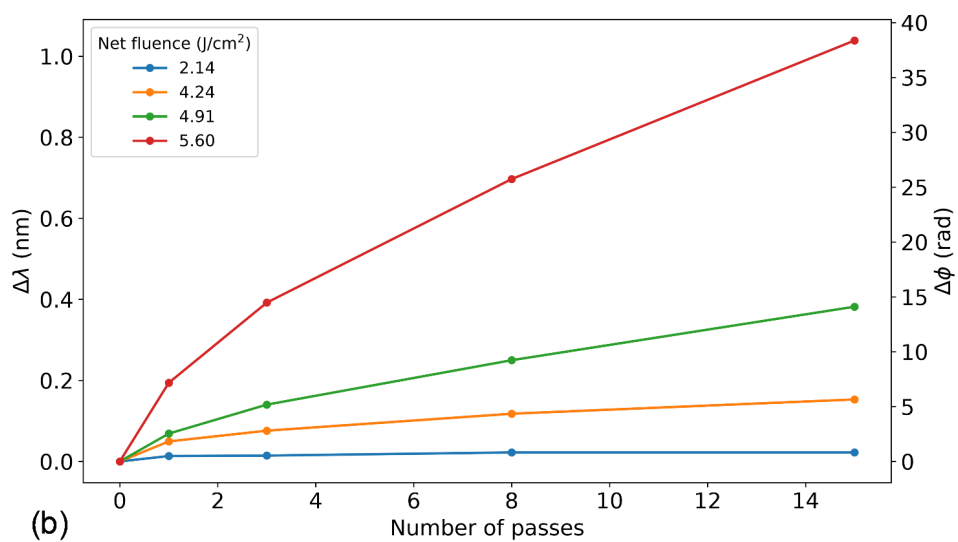
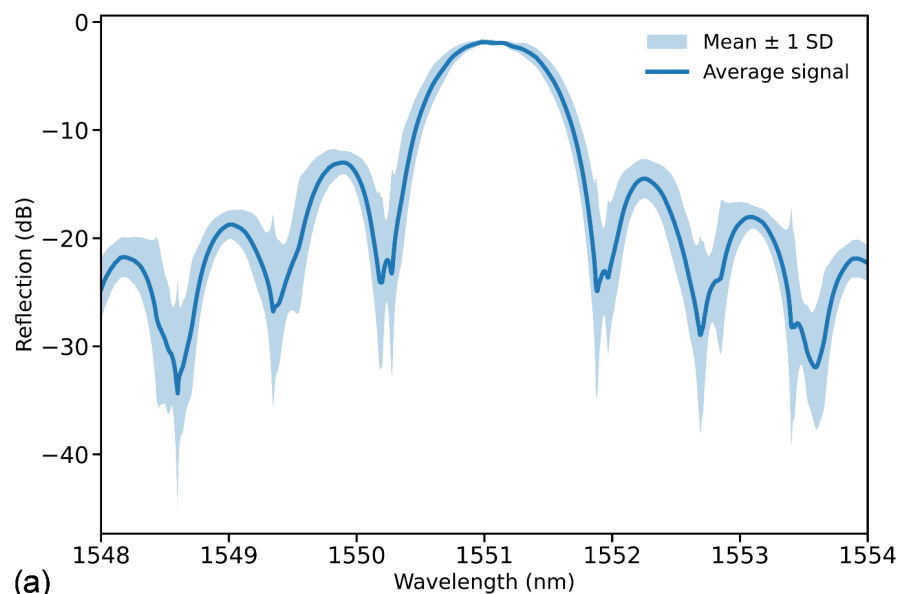


Fig. 2 (a) Mean reflection spectrum of ten FBGs inscribed under identical conditions; the shaded region represents ± 1 standard deviation. (b) Accumulated Bragg-wavelength shift and the corresponding calculated phase shift as function of the number of passes for net fluence ranging from 2.14 J/cm^2 to 5.60 J/cm^2

4. MICHELSON FILTER

The studied device is an interferometric multiplexer in which the FBGs are inscribed directly after the 3 dB coupler, as illustrated in Fig. 9(a). This compact, monolithic configuration minimizes the device length and improves its mechanical and phase stability. The demonstrated Michelson filter also represents an initial step toward the development of an all-fiber Mach–Zehnder multiplexer. Using the optimized fabrication recipe, a complete Michelson filter was integrated into a packaged device with a total length of 75 mm. The 10 mm long apodized FBGs inscribed in both branches of the coupler. The grating apodization envelope and phase profile are shown in Fig. 9(b). The FBGs were written at a translation speed of 0.05 mm/s using 150 pulse bursts with a pulse energy of 885 nJ. This process produced gratings with a reflectivity of more than 99 %, a transmission below -20 dB, and a spectral bandwidth of 290 pm. The two gratings exhibited highly similar spectral responses and good fabrication repeatability, with a Bragg wavelength mismatch of about 128 pm. This small residual difference may arise from longitudinal fiber nonuniformities or minor errors in the identified core positions. Despite the equal grating lengths and their symmetric placement relative to the coupler, a residual phase mismatch remained between the two interferometer branches. The initial return loss and drop output spectra before phase correction are presented in Fig. 9(c). The multiple peaks that have appeared in the return loss spectrum are due to the wavelength mismatch between two FBGs. To compensate for this mismatch, a uniform DC refractive-index modification was introduced on one of the FBGs using fs laser exposure. Afterward, a uniform waveguide is inscribed between FBGs and 3 dB coupler. This modification adjusts the optical path length of one branch and, consequently, the relative phase between the interfering signals. After phase trimming, the optimized spectral response shown in Fig. 9(d) was obtained, with an enhanced drop efficiency of more than 30 dB.

5. CONCLUSION

Compact all-fiber solutions are presented for multiplexing high power channels using fiber interferometers. High-performance fused couplers are realized to make Michelson and Mach-Zehnder fiber interferometers. The interferometers are made by fusing one or two couplers on two parallel fibers, making them compact and stable. The couplers are optimized to have 50% coupling ratio at a predetermined wavelength. A MZI with a contrast of 35 dB was demonstrated. The interferometers are bonded on slotted aluminum substrate giving access to the two parallel fibers to write identical FBGs on each fiber. A 50W High power testing of a non-heatsinked low-loss coupler showed a less than 7°C increase at the exit bond point. A point-by-point fs writing method was used to write each FGB. The method was improved to localize the fiber core positions before writing the gratings. The phase adjustment of the interferometers is also achieved with the fs writing. A transmission filter based on a Michelson configuration was fabricated and shown a 30 back-reflection. All the process improvement shown herein demonstrate the feasibility of an all-fiber solution for multiplexing into a single-mode fiber high power channels at more than 100 W.

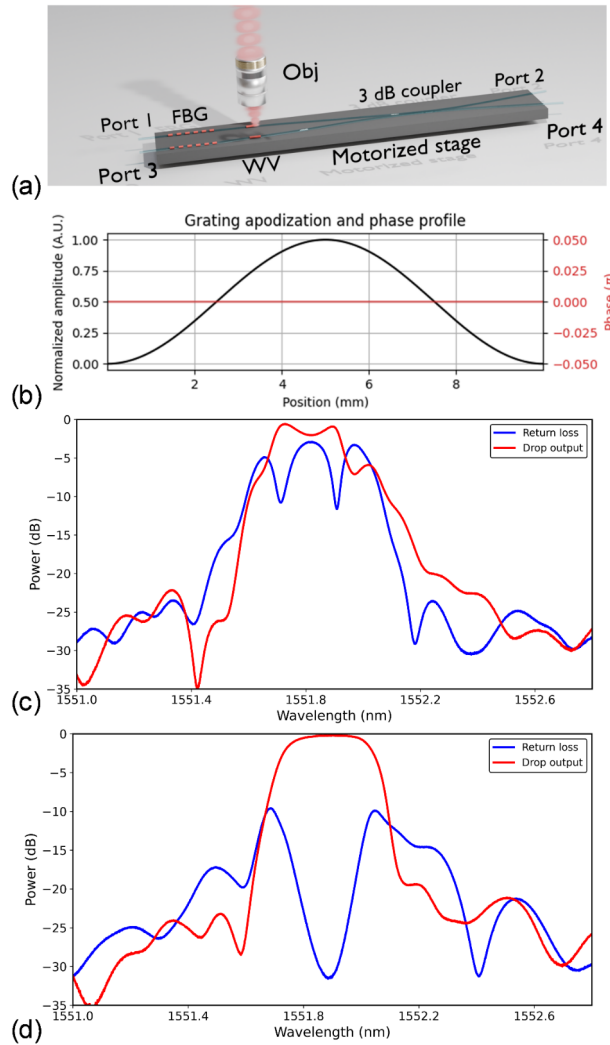


Fig. 3 (a) Schematic of the fs laser inscription arrangement for writing the FBGs and waveguide (WV) phase-trimming section in interferometer branches; the four coupler ports are indicated. The input signal is launched into Port 2, and the drop output is measured at Port 4. (b) Normalized grating-apodization envelope and phase profile used for FBG inscription. (c) Measured return loss and drop port spectra before phase trimming. (d) Corresponding spectra after phase trimming, showing an enhanced drop efficiency.

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