Femtosecond laser writing of a flat-top interleaver via cascaded Mach-Zehnder interferometers

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Abstract: A flat-top interleaver consisting of cascaded Mach-Zehnder interferometers (MZIs) was fabricated in bulk glass by femtosecond laser direct writing. Spectral contrast ratios of greater than 15 dB were demonstrated over a 30 nm bandwidth for 3 nm channel spacing. The observed spectral response agreed well with a standard transfer matrix model generated from responses of individual optical components, demonstrating the possibility for multi-component optical design as well as sufficient process accuracy and fabrication consistency for femtosecond laser writing of advanced optical circuits in three dimensions.

OCIS codes: (320.2250) Femtosecond phenomena; (350.2460) Filters, interference.

References and links

1. G. Della Valle, R. Osellame, and P. Laporta, “Micromachining of photonic devices by femtosecond laser pulses,” J. Opt. A, Pure Appl. Opt. 11(1), 013001 (2009).
2. R. R. Gattass and E. Mazur, “Femtosecond laser micromachining in transparent materials,” Nat. Photonics 2(4), 219–225 (2008).
3. S. Nolte, M. Will, J. Burghoff, and A. Tuennermann, “Femtosecond waveguide writing: a new avenue to three dimensional integrated optics,” Appl. Phys., A Mater. Sci. Process. 77(1), 109–111 (2003).
4. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, “Writing waveguides in glass with a femtosecond laser,” Opt. Lett. 21(21), 1729–1731 (1996).
5. C. Florea and K. A. Winick, “Fabrication and characterization of photonic devices directly written in glass using femtosecond laser pulses,” J. Lightwave Technol. 21(1), 246–253 (2003).
6. D. Homoeille, S. Wieland, A. L. Gaeta, N. F. Borrelli, and C. Smith, “Infrared photosensitivity in silica glasses exposed to femtosecond laser pulses,” Opt. Lett. 24(18), 1311–1313 (1999).
7. A. M. Streltsov and N. F. Borrelli, “Fabrication and analysis of a directional coupler written in glass by nanojoule femtosecond laser pulses,” Opt. Lett. 26(1), 42–43 (2001).
8. L. A. Fernandes, J. R. Grenier, P. R. Herman, J. S. Aitchison, and P. V. S. Marques, “Femtosecond laser fabrication of birefringent directional couplers as polarization beam splitters in fused silica,” Opt. Express 19(13), 11992–11999 (2011).
9. H. Zhang, S. M. Eaton, J. Li, and P. R. Herman, “Type II femtosecond laser writing of Bragg grating waveguides in bulk glass,” Electron. Lett. 42(21), 1223–1224 (2006).
10. R. Keil, M. Heinrich, F. Dreisow, T. Pertsch, A. Tünnermann, S. Nolte, D. N. Christodoulides, and A. Szameit, “All-optical routing and switching for three-dimensional photonic circuitry,” Sci Rep 1, 94 (2011).
11. Y. Sikorski, A. A. Said, P. Bado, R. Maynard, C. Florea, and K. A. Winick, “Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses,” Electron. Lett. 36(3), 226–227 (2000).
12. S. Taccheo, G. Della Valle, R. Osellame, G. Cerullo, N. Chiado, P. Laporta, O. Svelto, A. Killi, U. Morgner, M. Lederer, and D. Kopf, “Er:Yb-doped waveguide laser fabricated by femtosecond laser pulses,” Opt. Lett. 29(22), 2626–2628 (2004).
13. K. Minoshima, A. Kowalevicz, E. Ippen, and J. Fujimoto, “Fabrication of coupled mode photonic devices in glass by nonlinear femtosecond laser materials processing,” Opt. Express 10(15), 645–652 (2002).
14. G. Li, K. A. Winick, A. A. Said, M. Dugan, and P. Bado, “Waveguide electro-optic modulator in fused silica fabricated by femtosecond laser direct writing and thermal poling,” Opt. Lett. 31(6), 739–741 (2006).
15. G. D. Marshall, A. Politi, J. C. F. Matthews, P. Dekker, M. Ams, M. J. Withford, and J. L. O’Brien, “Laser written waveguide photonic quantum circuits,” Opt. Express 17(15), 12546–12554 (2009).
1. Introduction

In recent years, much effort has been directed towards improving laser control of femtosecond waveguide writing for creating optical devices for applications in optical telecommunications. Femtosecond laser writing has advantages over traditional fabrication techniques because it is flexible enough to create and integrate multiple 3D photonic devices into a single transparent substrate [1–3]. A variety of passive optical devices have been demonstrated with femtosecond laser writing including waveguides [4,5], power splitters [6], directional couplers [7], polarization splitters [8] and Bragg gratings [9]. Active routing and switching has been demonstrated in fused silica [10] while waveguides written in active media have produced optical amplifiers [11] and lasers [12] when integrated with fiber systems. These individual building blocks open up a wide range of possibilities for more highly functional integrated photonic devices, but so far, only simple interferometers [13,14] or directional couplers for quantum communication [15] have been demonstrated.

The integration of laser written optical components into functional optical microsystems presents a formidable challenge, owing to higher waveguide loss at 0.5 dB/cm [8] compared with planar lightwave circuit (PLC) fabrication methods of < 0.1 dB/cm [16], together with limited process control to compensate for wavelength dependence, dispersion, phase offsets, and birefringence. Unlike the advanced design and manufacturing finesse available in today’s fiber and PLC engineering, femtosecond laser writing poses its own unique challenges in managing optical loss in variously directed waveguide paths and in controlling waveguide mode size and birefringence through a myriad of laser exposure parameters such as pulse duration, polarization [17], focusing power, or pulse front tilt [18] that collectively drive a unique material response.
Amongst various functions such as optical switching, power splitting, and multiplexing found in higher level integrated optical circuits, the interleaver serves as a passive optical filter in dense wavelength division multiplexing (DWDM) to spectrally combine multiple communication channels. A flat-top interleaver (FTI) is preferred for the widened passbands that improves signal-to-noise and reduces channel cross-talk compared with simple MZIs [16]. FTIs are characterized as finite (FIR) and infinite impulse response (IIR) filters, where the latter relies on resonance interference. FIR filters have been demonstrated with fiber gratings [19] and cascaded MZIs [16], while IIR filters include Mach-Zehnder ring-resonator interferometers (MZIRRs) [20], and Michelson-Gires-Tournois interferometers (MGTIs) [21]. In general, IIR filters offer more attractive flat-top responses with higher contrast ratios [22], while FIR filters are known for their reliability and simplicity, and have higher potential for integration into photonic circuits [16]. Cascaded MZI FTIs have been demonstrated in PLCs [16], but not in laser written devices.

Building upon existing laser recipes and preliminary work on FTI [23], we extend femtosecond laser processing to create a more advanced integrated optical circuit in bulk glass. An FTI was designed and fabricated from a combination of various directional couplers (DCs) and MZIs. Loss, phase delay, coupling strength and wavelength dependence were characterized to facilitate an accurate modeling design that could balance trade-offs between loss, component size, and process variability and thereby deliver an optimized FTI design across a broad spectral window. Despite moderate variability in the laser process and component responses, the modeling permitted an FTI device to be fabricated by direct laser writing. Hence, the feasibility for laser writing to form highly functional integrated multi-component photonic systems has been demonstrated.

2. FTI modeling

An integrated four-port FTI circuit based on two cascaded MZIs was selected that combines several four-port optical devices including the three DCs as seen in Fig. 1.

An optimized FTI design required the free spectral range (FSR) of the two resulting MZIs to differ by a factor of two. The FTI design following a standard transfer-matrix method based on a 2 x 2 system matrix, \( M_{FTI} \), to relate the output electric fields (\( E_3 \) and \( E_4 \) at ports 3 and 4, respectively) to the input fields (\( E_1 \) and \( E_2 \) at ports 1 and 2, respectively):
\[
\begin{pmatrix}
E_3 \\
E_4
\end{pmatrix}
= M_{\text{FTI}}
\begin{pmatrix}
E_1 \\
E_2
\end{pmatrix}
\]  
(1)

The overall system transfer matrix for the present four-port FTI,

\[
M_{\text{FTI}} = M_{\text{DC}_1} \left( M_{\Delta \theta_1} , M_{\alpha_1} \right)_{\text{MZI}_1} \quad M_{\text{DC}_2} \left( M_{\Delta \theta_1} , M_{\alpha_1} \right)_{\text{MZI}_2} \quad M_{\text{DC}_3} \quad M_{\text{DC}_4},
\]  
(2)

accounts for DC coupling responses as represented by \( M_{\text{DC}_1} \), \( M_{\text{DC}_2} \), and \( M_{\text{DC}_3} \), as well as the asymmetric propagation losses, \( M_{\alpha_1} \) and \( M_{\alpha_2} \), and the phase delays, \( M_{\Delta \theta_1} \) and \( M_{\Delta \theta_2} \), imposed by the two waveguide arms of each of MZI section. The power coupling ratio, \( r_j \), of the output ports, \( j = 3 \) or \( 4 \), were extracted from the square of the fields:

\[
\begin{align*}
 r_j (\lambda) &= \frac{P_j}{P_i} = \frac{E_j^2}{E_i^2 + E_2^2}, \quad j = 3, 4.
\end{align*}
\]  
(3)

2.1 Directional couplers

The DC layout as shown in the inset of Fig. 1 consists of circular waveguide segments to form symmetric S-bends that converge to parallel, symmetric waveguides, closely separated by coupling distance, \( d \), over a coupling length, \( L_c \). Following Eq. (3), the power coupling ratios for laser formed DCs were found to be well described by coupled mode theory (CMT) [24], according to the sinusoidal response:

\[
\begin{align*}
 r_j (\lambda) = A \sin^2 \left[ \theta_{\text{DC}} (L_c, \lambda) \right], \quad j = 3, 4,
\end{align*}
\]  
(4)

where \( \theta_{\text{DC}} (L_c, \lambda) = \kappa (\lambda) L_c + \phi (\lambda) \).

Here, \( \kappa (\lambda) \), is the coupling strength between the waveguides that depends on the waveguide separation distance and mode overlap, \( \phi (\lambda) \) is an additional phase shift to account for coupling in the S-bends, and \( A \) is the maximum power transfer ratio that is expected to equal one for the present case of symmetric waveguides [25]. Although \( L_c \) can be easily varied in the circuit design to provide an optimum DC splitting ratio, \( r_j \), both the magnitude and the wavelength dependence in \( \kappa (\lambda) \) and \( \phi (\lambda) \) are highly varied with the waveguide layout and laser exposure conditions [24,25] that can dramatically limit the useful spectral bandwidth of the FTI. Finally, since propagation losses through the DC were symmetric in both waveguide arms and small (< 0.1 dB) relative to the other FTI losses, these symmetric losses could be ignored in the overall FTI response, yielding the following transfer matrix for the lossless DC:

\[
M_{\text{DC}} = \begin{pmatrix}
\cos \theta_{\text{DC}} & i \sin \theta_{\text{DC}} \\
-i \sin \theta_{\text{DC}} & \cos \theta_{\text{DC}}
\end{pmatrix}
\]  
(5)

2.2 MZI response

The MZI spectral response was separated into a phase response, \( M_{\Delta \theta_1} \), and a propagation loss response, \( M_{\alpha} \), shown below:
The path difference, \( \Delta L \), between the waveguide arms combined with the effective index, \( n_{\text{eff}}(\lambda) \), of the device introduces a relative phase delay, \( \Delta \theta_p \), between the waveguide arms, which results in a spectral fringe pattern. The propagation losses depend on the straight and curved decay constants \( \alpha_s(\lambda) \) and \( \alpha_c(\lambda) \) and the lengths of these sections, \( L_s \) and \( L_c \), respectively.

The MZI arms differed greatly in the proportion of straight and curved sections, which results in strongly asymmetric losses between the arms. This dramatically alters the power ratio in waveguides entering subsequent DCs, reducing the channel contrast.

3. Laser writing and characterization of waveguides

The various waveguide devices were written in bulk fused silica glass (3” × 2” × 1 mm) with a frequency doubled femtosecond fiber laser (IMRA µJewel D-400-VR) at 522 nm wavelength. Laser exposure parameters were optimized as described in previous work [8,23–26] to values of 220 fs pulse duration, 1 MHz repetition rate, and 120 nJ per pulse energy to provide low propagation and coupling loss to single mode fiber via mode size matching (10.4 µm mode field diameter at 1550 nm). The writing laser was polarized parallel to the scan direction and focused to a depth of 100 µm below the glass surface with a 0.55 NA aspherical lens while air-bearing translations stages (Aerotech ABL1000) were used to control the glass slide motion relative to the focus position. Straight sections were scanned at 0.5 mm/s according to previous work [23] while curved sections were optimized to 0.3 mm/s to minimize bend loss.

The laser-written photonic devices were probed with a broadband light source (Agilent 83437A) over the 1250 to 1650 nm spectral range by free space launching (0.3 NA lens) into the entrance waveguide while the light exiting the device was end coupled into a single mode fiber for capturing transmission spectra with an optical spectrum analyzer (Ando AQ6317B). Index matching oil was used at the fiber-to-waveguide interfaces to reduce Fresnel reflection loss. A free-space linearly polarizer permitted excitation of pure vertically or horizontally polarized modes that was necessary to separate polarization dependent responses associated with an expected waveguide birefringence of \( n\Delta \sim 5 \times 10^{-5} \) [8]. All spectral responses were normalized in the same way against a reference straight waveguide with known insertion loss.

4. FTI design

The FTI was developed through successive stages of laser fabrication and characterization of individual waveguides and four-port DC and MZI devices, to construct the transfer matrix response functions in Section 2. A range of laser exposure conditions was explored to minimize waveguide loss while also seeking a small bend radius for compactness of the back-to-back MZI design to fit over a 3” wide glass substrate. With these constraints, a channel spacing of 3 nm was targeted together with DC coupling ratios of 50.0%, 72.8%, and 92.6% that were previously optimized [27] to generate wide flat-top passbands with deep contrast.
ratios. A convergence of the measured and simulated spectral response was finally sought to provide a balanced interleaver response over the broadest spectral window.

4.1 Optical losses

Straight and curved waveguides of multiple lengths and radii were characterized to extract coupling and propagation losses from insertion loss data. Extrapolation of the loss data to zero-length yielded coupling losses that increased with wavelength, from 0.50 to 0.67 dB/facet over the 1250 to 1400 nm spectral range. Insertion losses closely followed an exponential dependence on waveguide length, providing the propagation loss data, $\alpha(R,\lambda)$, as shown in Fig. 2 for the straight and curved ($R = 35$ mm and 75 mm) waveguides across the 1250 to 1500 nm spectrum. Straight waveguide losses decreased moderately from 0.93 to 0.37 dB/cm towards longer wavelength while bend losses rose nearly exponentially from 0.58 to 2.1 dB/cm for 75 mm radius waveguides and more steeply from 0.35 to over 8 dB/cm for 35 mm radius waveguides. While Rayleigh scattering is anticipated to account for the majority of loss in straight waveguides [25], the trend of increasing mode size with longer wavelength underpins the exponential-like increase seen in Fig. 2 for curved waveguides, following the expected trends of both infinite cladding models [28] and single-mode fiber bending loss [29]. However, overall losses are much higher here than found in planar lightwave circuits due to a three-fold weaker induced index contrasts of $\Delta n \approx 0.01$ [30] and overall roughness in the waveguide morphology generated by femtosecond laser interactions. An apparently anomalous trend in propagation loss, decreasing from 0.93 dB/cm for straight waveguides to 0.35 dB/cm for the smallest radius waveguide, arises when narrowed modes within bend regions shift partially outside the index modification zone to reduce optical scattering [29].

The FTI design was focused in the 1250 to 1325 nm range of Fig. 2, where propagation loss of all the straight and curved waveguides was lowest (< 1.00 dB/cm). Design wavelengths of 1310 nm and 1391 nm were identified for the 35 mm and 75 mm radius waveguides, respectively, that would provide nearly identical propagation losses of 0.71 dB/cm and 0.94 dB/cm, respectively, for balancing losses in the both arms of each MZI. While the lower loss and flatter wavelength response of the larger 75 mm radius waveguides would provide a broader interleaver spectrum, the lower 35 mm radius waveguides were
selected for both the DC and MZI curved sections to provide a five-fold denser channel spacing and more compact design. The propagation loss data in Fig. 2 provided the \( \sigma_j(R = \infty, \lambda) \) and \( \sigma_j(R = 35 \text{ mm}, \lambda) \) matrix elements required in Eq. (7).

To counter modal offset losses [31] at the inflection points where waveguide curvature is flipped or meets straight waveguides, the circuit design in Fig. 1 was modified to offset waveguides by 0.8 or 0.4 µm, respectively, and reduced loss by an average of 0.16 dB per inflection point. Other means to reduce such transition loss by writing waveguides with varying radius (i.e. sinusoidal) or width were not explored. Additional transition losses were expected to arise from using two different scan speeds that yield slightly different mode sizes and refractive index profiles, but these losses were more than offset by the net improvement (~0.7 dB) in transmission in curved sections written at lower speed.

4.2 Directional couplers

To characterize the directional coupler response under the current laser writing conditions, a series of symmetric DCs were written with the minimum waveguide separation fixed at \( d = 8 \) µm and coupling lengths varied from \( L_c = 0 \) to 2 mm in 0.2-mm steps. Figure 3 shows the measured coupling ratios calculated from Eq. (3) for 1310 nm and fitted according to Eq. (4) to yield \( \kappa(\lambda) \), \( \varphi(\lambda) \), and \( A(\lambda) \) values of 1.398 mm\(^{-1} \), 1.021, and 0.994, respectively, for port 3. This corresponds to a beat length of 2.247 mm that permitted selection of any DC coupling ratio \( (r = 0 \text{ to } 1) \) up to a high 25-dB contrast ratio for coupling lengths under 1.124 mm. Interpolation of the present data offered coupling lengths of \( L_c = 0.955, 0, \) and 0.230 mm to meet the respective 50.0%, 72.8%, and 92.6% coupling ratios required in the present FTI design for operation around 1310 nm.

![Fig. 3. The measured coupling ratio, \( r \), at 1310 nm for DCs of various coupling lengths and the representation of Eq. (4) (solid lines) with DC matrix parameters: \( \kappa = 1.398 \text{ mm}^{-1}, \varphi = 1.021, \) and \( A = 0.944 \) and a coefficient of determination, \( R^2 = 0.99956. \)](image)

The DC spectral response, \( r(\lambda) \), for a 3-dB coupler design at 1310 nm was assessed as shown in Fig. 4, yielding a relatively flat wavelength dependence of 3.0 ± 0.5 dB (50 ± 5%) between 1296 to 1326 nm that predicts a 30-nm spectral window for favorable FTI response.

4.3 MZI response

For waveguides limited to 35 mm bend radius, the maximum path differences that could be generated over the present substrate was \( \Delta L_1 = 192.92 \) µm and \( \Delta L_2 = 385.84 \) µm for the cascaded MZI to yield a minimum FTI channel bandwidth of 3 nm at 1310 nm. Larger
channel separation can be arbitrarily designed with smaller path differences, up to the symmetric $\Delta L = 0$ case. The phase delay between the MZI arms was precisely modeled by extracting a linear estimate of $n_{\text{eff}}(\lambda) = 1.4736 - 1.7891 \times 10^{-5} \lambda$ from the fringe spacing in an MZI over the 1250 to 1350 nm range. Given the small refractive index modification induced by laser writing, the waveguide contribution to the chromatic dispersion will be much less than that of the material dispersion. We therefore expect the chromatic dispersion of the device in the region of its flat passbands to follow that of fused silica.

The spectral response of a single DC with coupling length, $L_c = 0.955$ mm, yielding a nearly flat $3.0 \pm 0.5$ dB coupling ratio over a 30-nm bandwidth between 1296 and 1326 nm.

5. Interleaver prototype

The spectral response of the FTI design for the optimized waveguide device parameters in Section 4 were calculated from the FTI matrix response in Eq. (2) and plotted in Fig. 5 (solid lines) together with the spectral response of the associated laser-fabricated FTI prototype (dashed lines). An accurate spectral alignment was found between the design and prototype channels for both output ports (3 and 4), coinciding within $\pm 0.01$ nm ($\pm 0.3\%$ of FSR) for the 1310 nm channel and increasing to $\pm 0.1$ nm ($\pm 3\%$) at 1269 nm and 1341 nm. A moderately strong contrast ratio of $> 15$ dB was maintained between the output ports across a 30-nm operating band from 1287 and 1317 nm, attesting to the high precision and reproducibility of laser fabrication without the need for phase trimming of the MZI arms. These contrast ratios fell $\sim 10$ dB short of the 25 dB design values expected near 1310 nm, potentially arising from small variations in the laser exposure control that lead to varied waveguide properties ($n_{\text{eff}}(\lambda)$ and $\alpha(\lambda)$), detuned DCs, or phase errors in the MZI arms. Moving away from the design wavelength, the coupling ratios for both measured and predicted responses became increasingly unbalanced due to the limited 30-nm bandwidth found in Fig. 4 for the present 3-dB coupler design. The contrast degrades further to $< 10$ dB for longer wavelengths, $\lambda > 1340$ nm, due to the strongly increased bend loss anticipated in the longer MZI waveguide arms by Fig. 2 ($R = 35$ mm) that unbalance the power ratios at the DCs. Nevertheless, a 10-dB contrast ratio was maintained on all FTI output ports over a large 70-nm range from 1270 to 1340 nm.

The flat-top response of the FTI in Fig. 5 was characterized by a 0.5-dB passband width of 1.85 nm for the 3-nm channel spacing at 1308 nm. An average 0.5-dB passband of 1.75 nm was found for the five channels in the 1290 to 1317 nm band, representing a 46% wider passband that meets closely with the 50% widening expected over a single MZI interleaver design. Outside of this spectral window, the 0.5-dB passband narrowed to values as low as 1.2 nm ($\lambda > 1338$ nm) and became double peaked ($\lambda < 1269$ nm) for the port 4 channels, owing to imbalance in the MZI arm loss, MZI phases, and DCs splitting ratio.
The propagation loss of the FTI shown in Fig. 2 was inferred from the insertion loss spectrum that gives a value of 9.3-dB loss at the 1310 nm design wavelength. The minimum propagation loss of 1.5 ± 0.1 dB/cm found in the 1250 to 1310 nm aligns well with the 1287 to 1317 nm operating range of the optimized interleaver response in Fig. 5. The interleaver loss increased strongly to > 3.6 dB/cm with longer wavelength, $\lambda > 1430$ nm, that followed the trend of losses for the $R = 35$ mm curved waveguide in Fig. 2.

Immersion of the FTI into ice water yielded a small 0.5 nm spectral shift from room temperature, illustrating a very small temperature dependence of $\approx 0.03$ nm/°C or 1% FSR/°C around 1310 nm.

6. Discussion and conclusion

Several directions are available for further improving the spectral response of the femtosecond laser written interleaver. A reduction of total insertion loss particularly towards longer wavelengths into the C- and L- telecom bands requires development of stronger guiding waveguides with bend loss falling well below the 5.0 dB/cm values seen in Fig. 2 for $\lambda > 1430$ nm. Femtosecond laser writing with high NA oil immersion lenses is one promising approach in this direction that offers two-fold smaller mode sizes (i.e. 7.2 µm mode field diameter) and two-fold higher refractive index contrast [30] such that higher curvature waveguides could be exploited for creating more compact MZI and FTI devices with higher channel isolation and denser channel spacing. The FTI bandwidth was restricted by the narrow 30-nm bandwidth in the present symmetric DC design (Fig. 4), while a 10-fold bandwidth improvement has been found previously with asymmetric DCs laser-written in borosilicate glass [24].

The FTI was analyzed for a single linear polarization to avoid birefringence ($\Delta n \approx 5 \times 10^{-5}$) [8] effects in the laser written waveguides. Harnessing heat-accumulation effects such as observed in waveguides formed in borosilicate glass [9] can offer much lower birefringence to aid in developing a polarization insensitive interleaver.

The flat-topped FTI response in Fig. 5 demonstrates the precision of matrix modeling as a design tool that can now be reliability applied to femtosecond laser writing of waveguides to develop more functional optical circuits. Design approaches were applied here to account for various loss, phase and power splitting imbalances and enable femtosecond laser writing in a single step process without complex trimming procedures. As the capabilities of femtosecond laser fabrication improve, this design approach will facilitate more practical device
applications into areas such as spectral shaping and polarization control or phase-array waveguide gratings to exploit the 3D advantage of the laser writing process.

In summary, the design optimization and fabrication of an integrated five-component flat-top interleaver was demonstrated by using femtosecond laser writing of optical waveguides in bulk glass. The laser processes and design were sufficiently robust to produce 46% widened 0.5-dB flat-top response with channel contrast ratios above 15 dB over a 30 nm bandwidth. Overall, the transfer matrix model successfully captured the phase and loss responses through multiple photonic components for predicting the spectral response of the FTI, with spectral alignment within ± 0.01 nm or 0.3% of the 3 nm channel spacing. The results demonstrate the accuracy and reproducibility of the femtosecond laser writing of more functional 3D optical circuits inside bulk transparent glass.

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