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Spatial Mode Demultiplexing of Femtocond-Inscribed Fiber Bragg Grating in Multi-Mode Fibers for High Temperature Sensing

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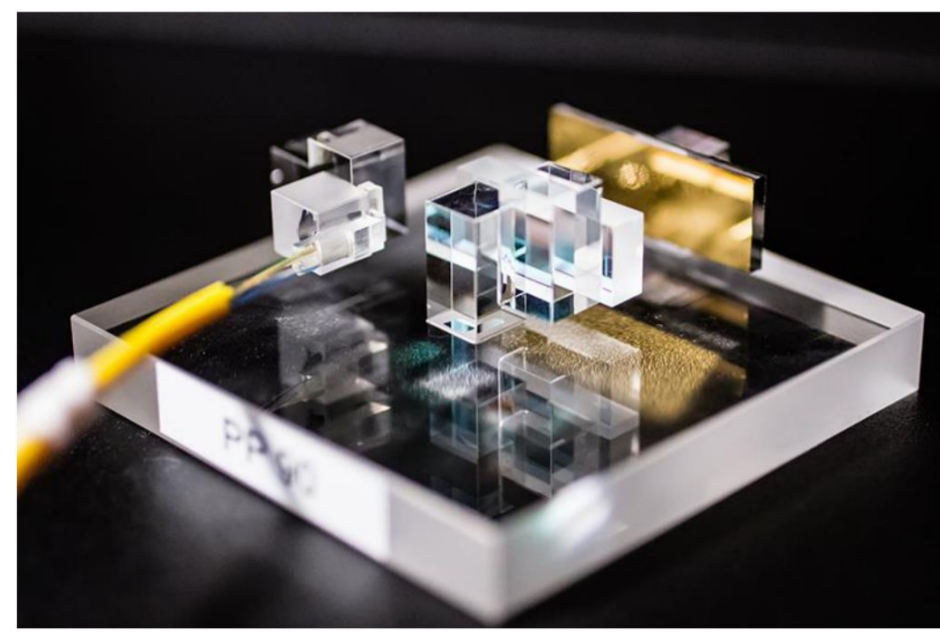
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Spatial DEMUX based on MPLC technology

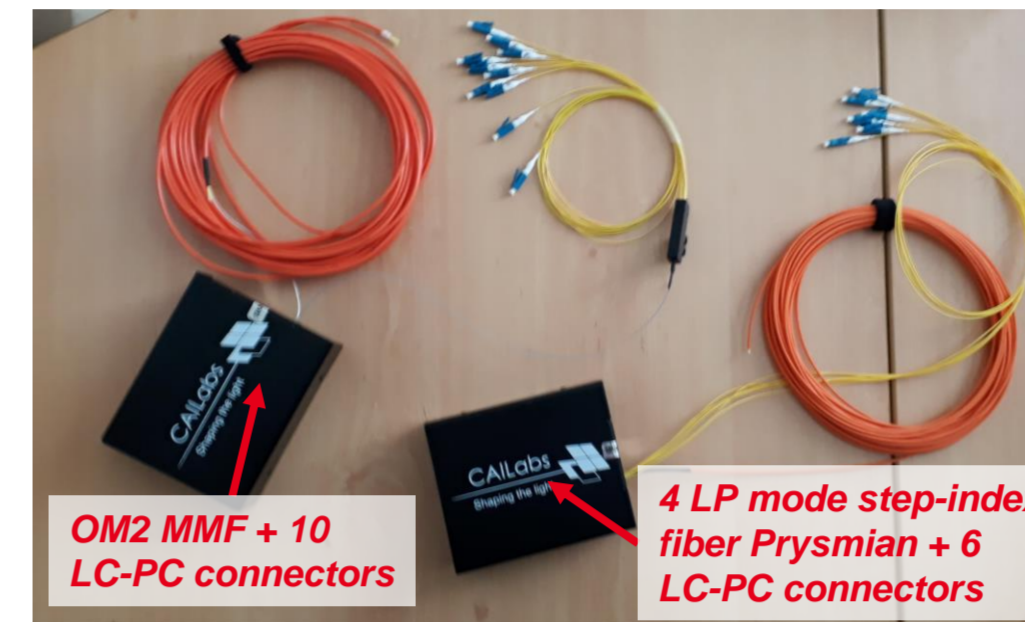
Cailabs Proteus spatial demultiplexer (DEMUX) based on Multi-Plane Light Conversion (MPLC) offers additional multiplexing capabilities for fiber optic sensing in multi-mode (MM) fibers (MMF) [1]. A single Fiber Bragg Grating (FBG) inscribed in MMF is able to excite multiple guided modes, generating FBG reflection peaks at different wavelengths. Different Proteus modules are presented below, corresponding to different MMFs, decomposition bases and numbers of channels.



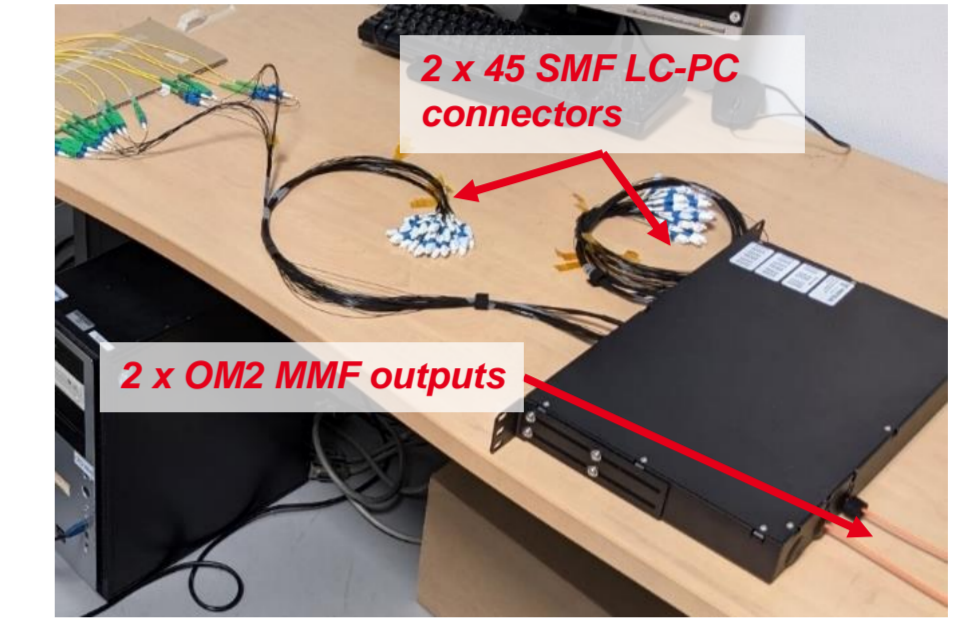
(a)

PARAMETERS	PROTEUS-S-6						PROTEUS-S-10		PROTEUS-S-15	
Description of the component	Space Division Multiplexer (MUX)									
Number of modes @1550 nm	6		10				15			
Mode types @1550 nm	LP ₁ , HG									
Wavelength	1550 nm (C-band)									
Insertion loss / Mux	Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Max.
	3 dB	4 dB	4.5 dB	5 dB	5 dB	6 dB	5 dB	6 dB	6 dB	6 dB
Crosstalk / Mux	Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Max.	Typ.	Max.
	-23 dB	-18 dB	-21 dB	-15 dB	-19 dB	-13 dB	-19 dB	-13 dB	-19 dB	-13 dB
Input fiber type	SMF-28e									

(b)



(a)



(b)

Fig 1. Photograph of MPLC optical setup (a) and specification of several Proteus modules (b).

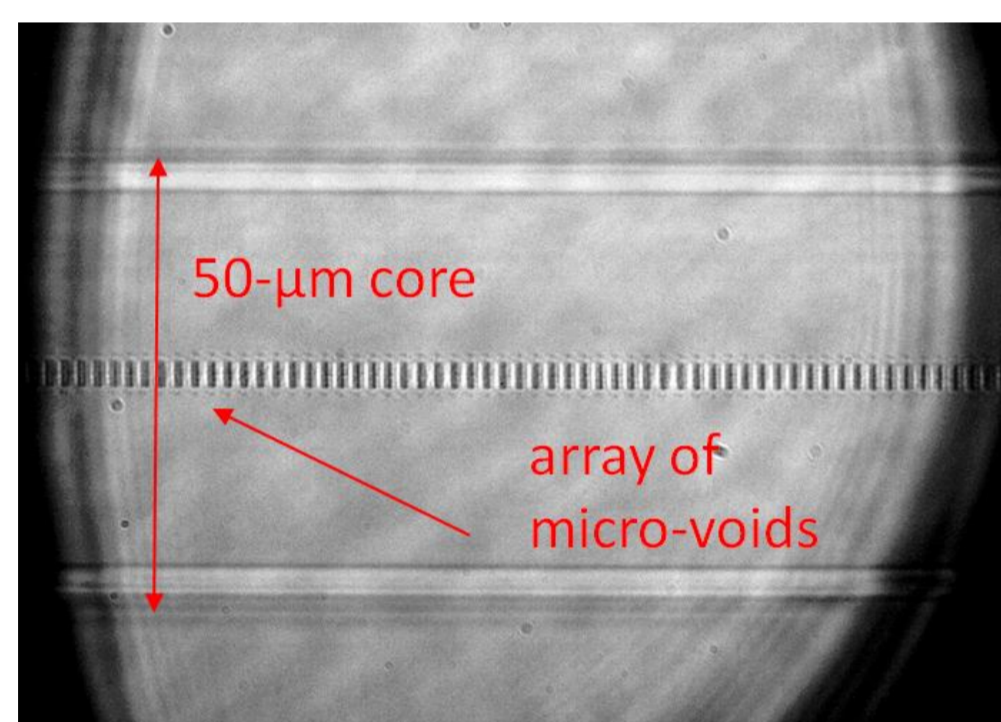
Fig 2. Photograph of different Proteus modules tested by CEA List. (a) Proteus S-6 and S-10 and (b) Custom rack-mounted package of two Proteus modules supporting 45 channels.

Interrogation of FBG inscribed in MMF with CEA List femtosecond laser platform

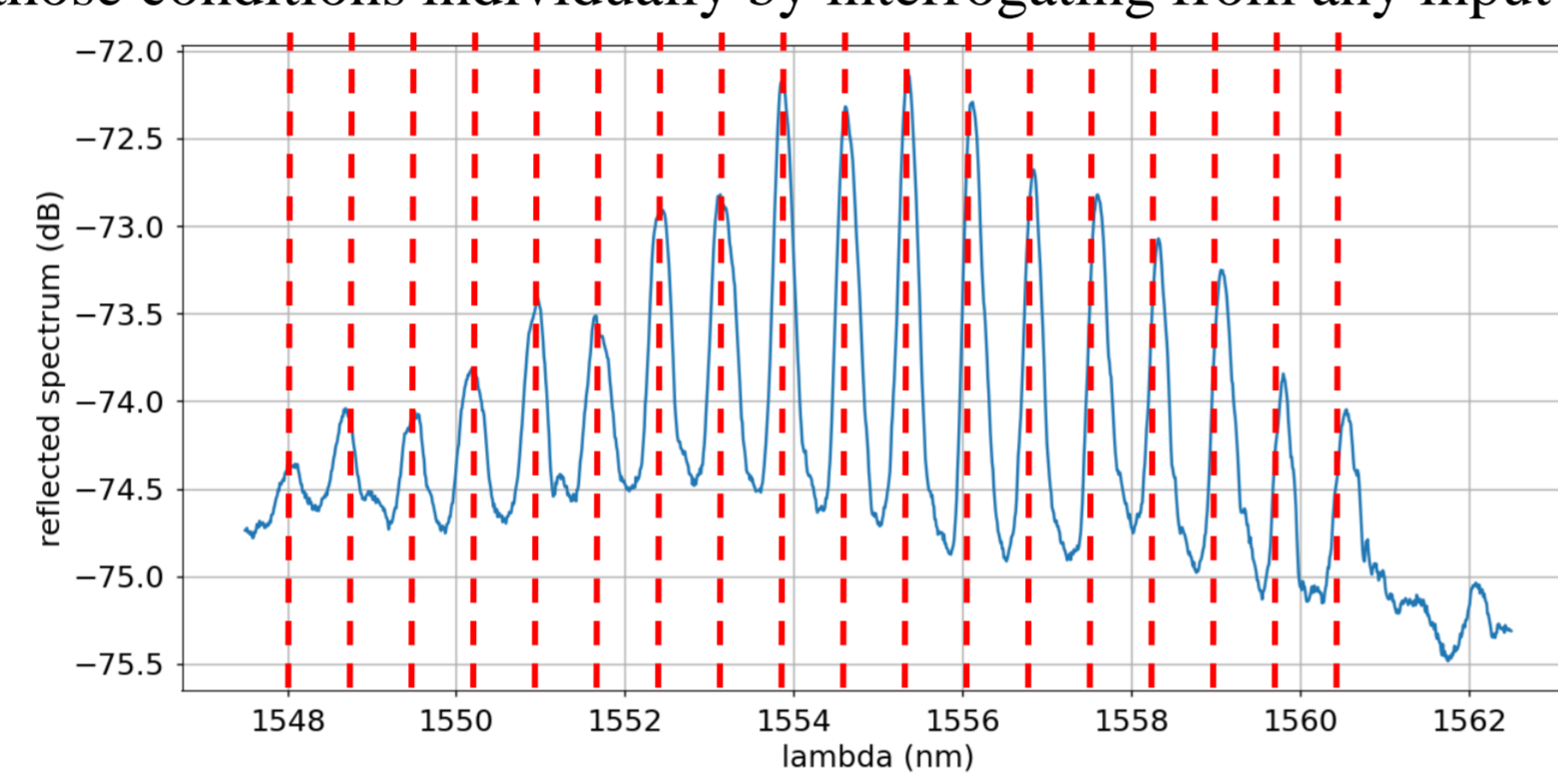
CEA List femtosecond laser platform is dedicated to fiber optic sensor fabrication for harsh environments [2, 3]. In particular, point-by-point (PbP) FBGs able to sustain High Temperatures (HT) [4, 5] are fabricated by focusing femtosecond laser pulses of tens to hundreds of nano-joules into the fiber core, producing an array of micro-voids at the desired pitch Λ and order k corresponding to the targeted FBG wavelength. In this section, direct interrogation of FBGs in MMF is compared to interrogation with Proteus according to different configurations.

Direct interrogation of FBG in MMF

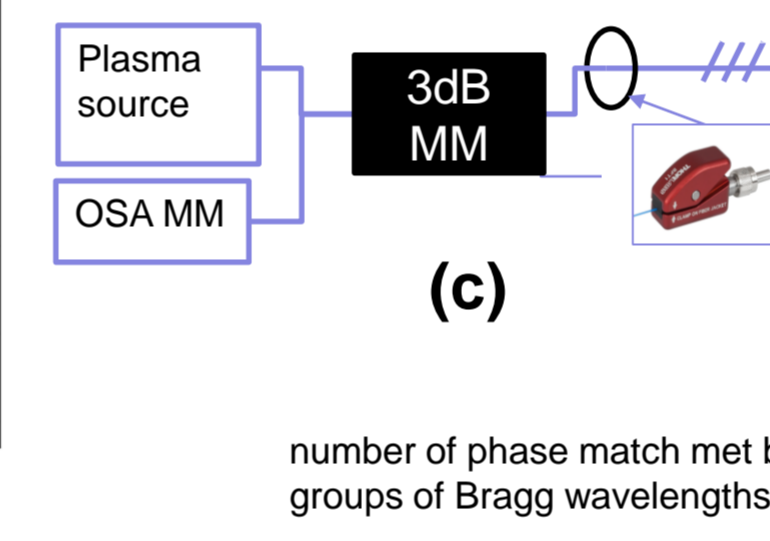
A photograph of a FBG inscribed in OM2 fiber is presented below. When interrogating such an FBG with adapted MM setup, a number of peaks can be observed on reflected spectrum. Each peak correspond to multiple phase match conditions between the different mode groups (MGs) off effective indices that propagate in the graded-index fiber ($n_{eff,i}$, i corresponding to one of the 10 MGs of the MMF under test). Cailabs Proteus enables to access each of those conditions individually by interrogating from any input MG to any output MG.



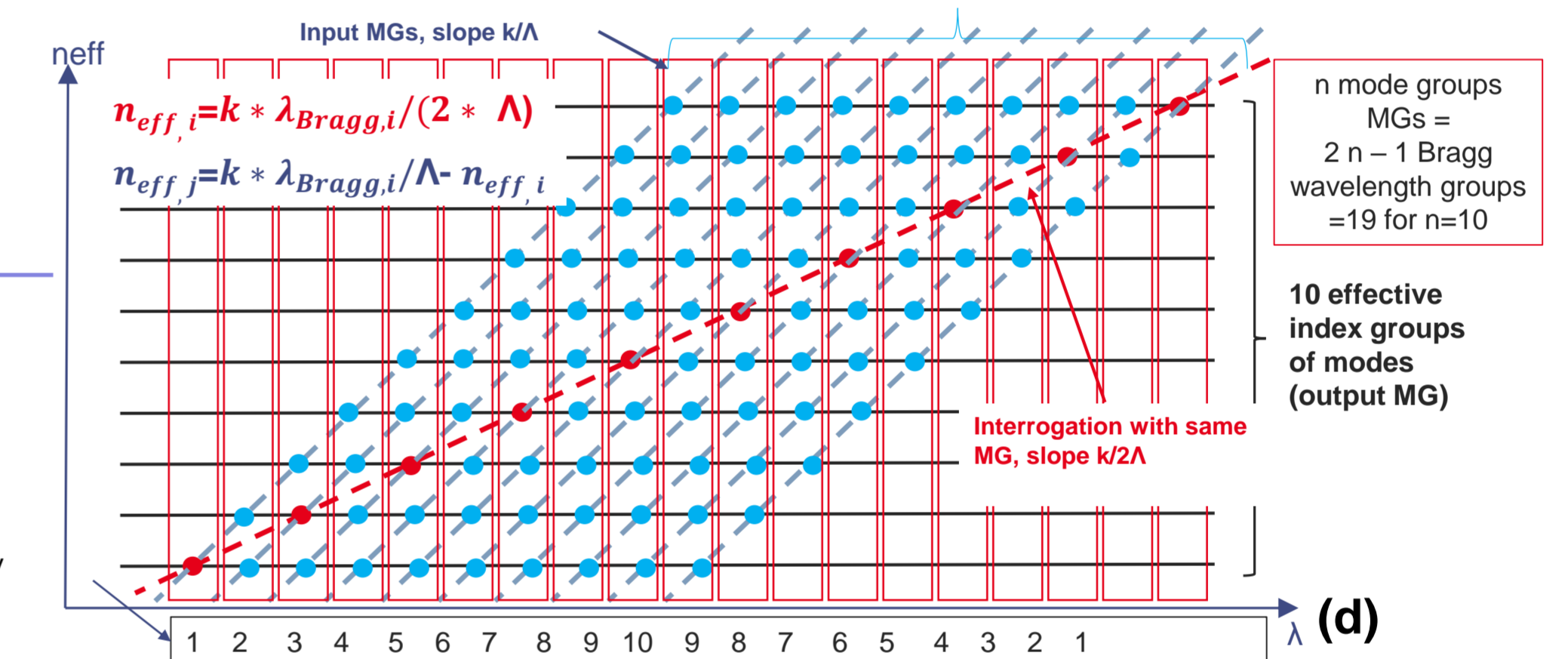
(a)



(b)



(c)



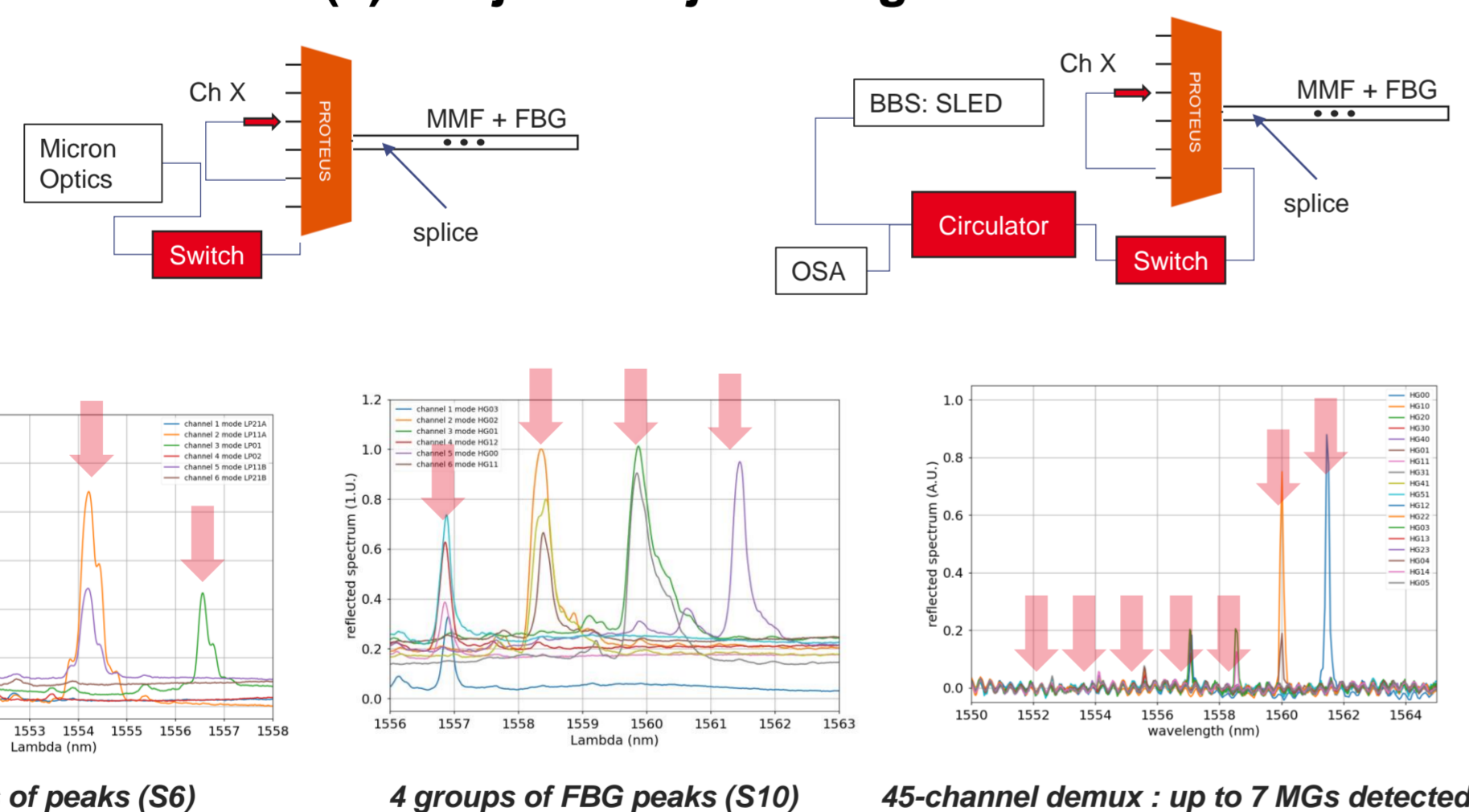
(d)

Fig 3. Photograph of FBG inscribed in OM2 fiber (a), reflected spectrum of single FBG (b), MMF interrogation setup (c) and schematic of phase match conditions occurring in 10-MG fiber according to the different phase match equations (d).

Interrogation with spatial demux: setups and FBG wavelength spacings

Two interrogation configurations are presented below. The first corresponds to interrogation with same mode as input and output while the second correspond to fundamental HG00 mode as input. In each case, reflection peaks are observed on the reflection spectrum at a position corresponding to the mode group of the selected output channel. One can notice that the spacing between groups of reflection peaks is divided by two in the second case, in accordance with the change of phase match equation.

(a) HG_{ij} => HG_{ij} interrogation



(b) HG00 => HG_{ij} interrogation

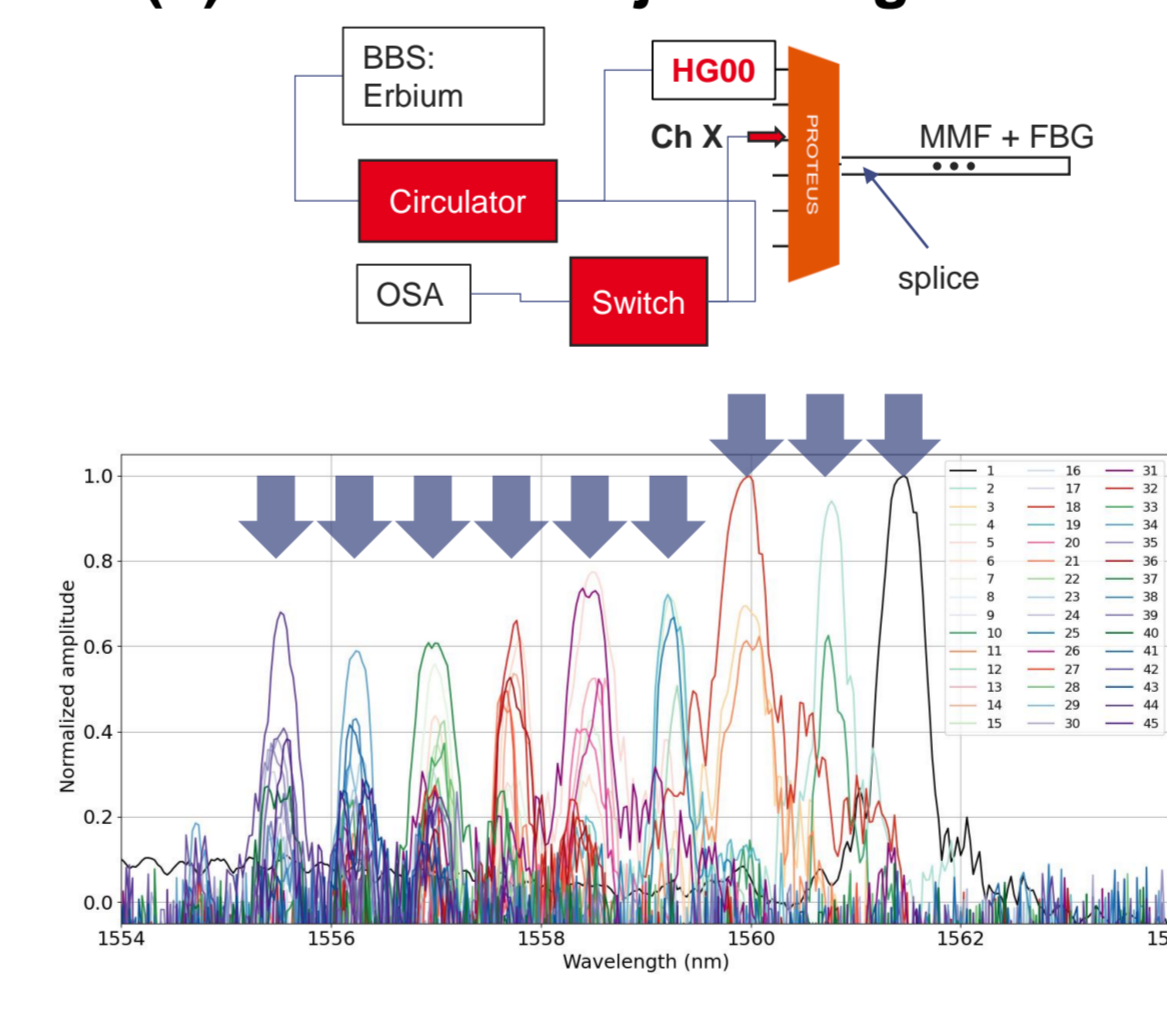


Fig 4. Reflected peaks corresponding to (a) HG_{ij} => HG_{ij} interrogation and (b) HG00 => HG_{ij} interrogation

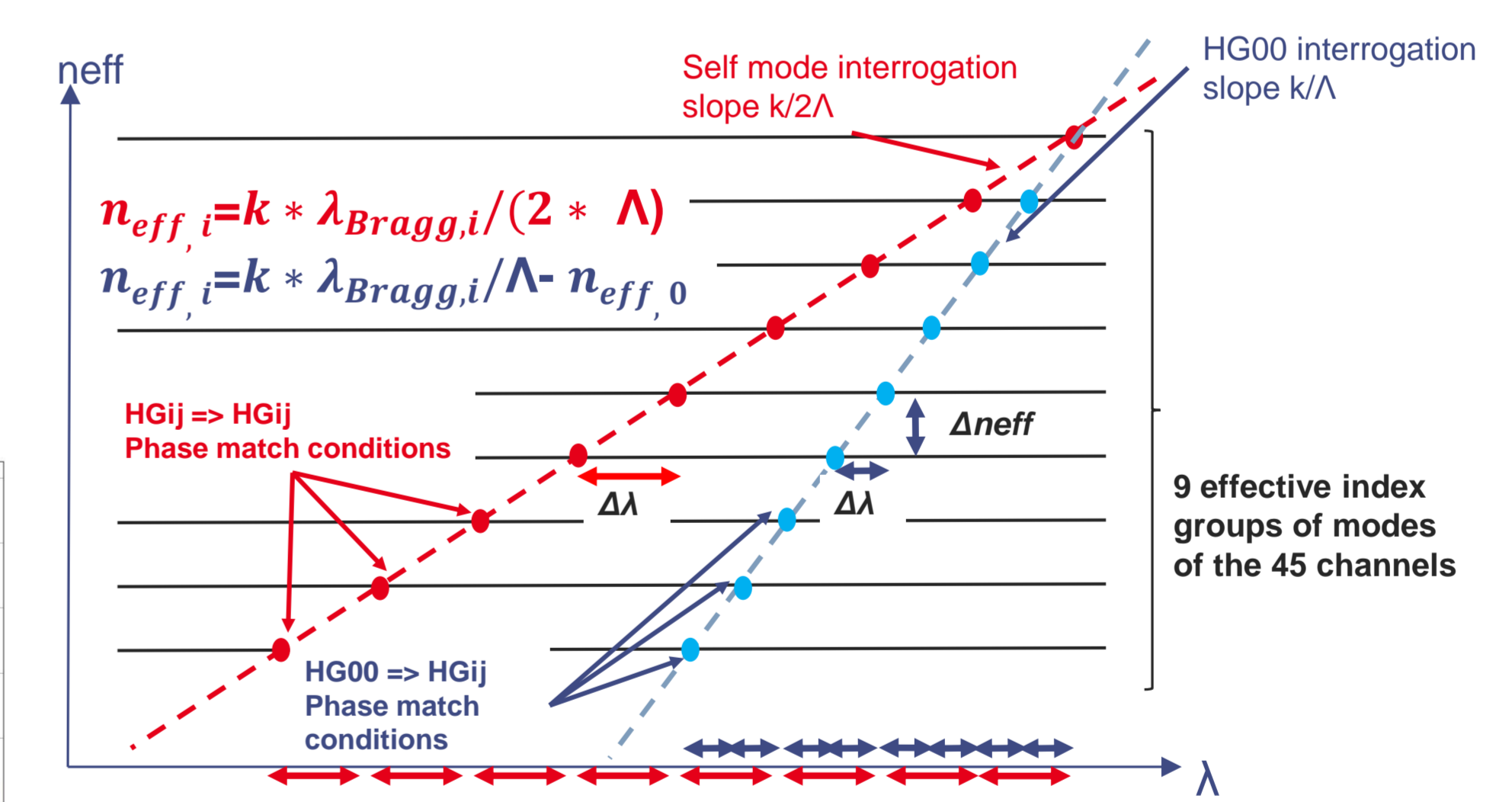
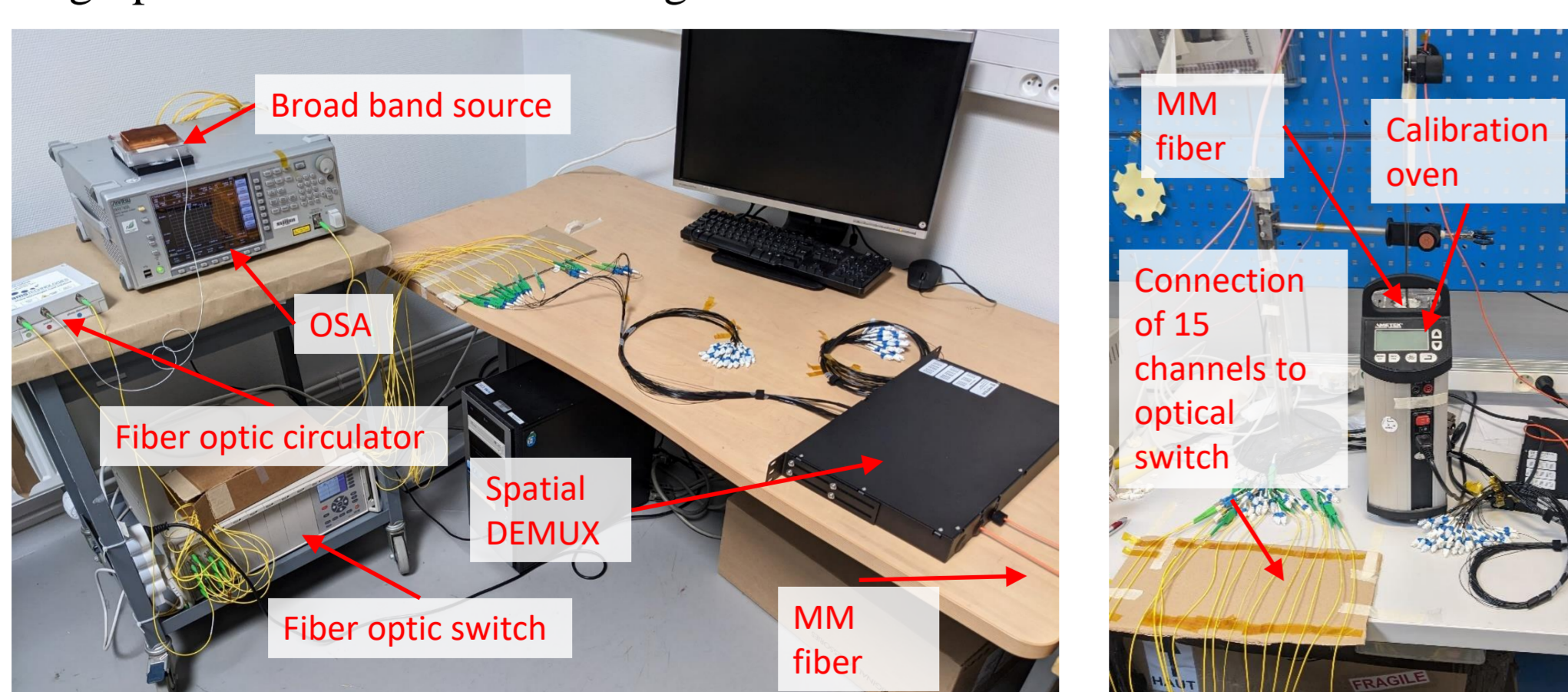


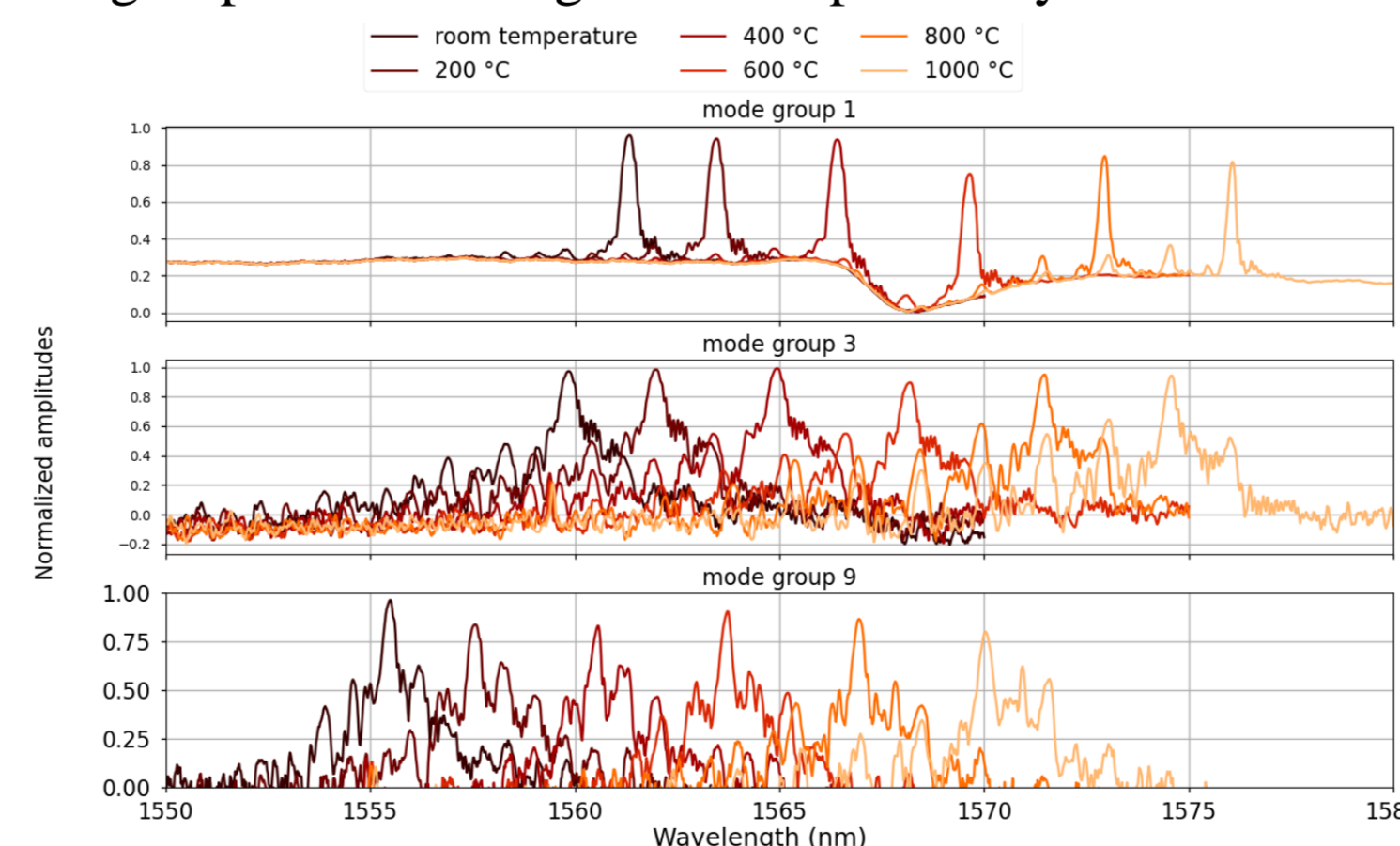
Fig 5. Schematic of the phase match conditions occurring for both interrogation configurations.

Interrogation of 15 channels during temperature steps of up to 1000 °C

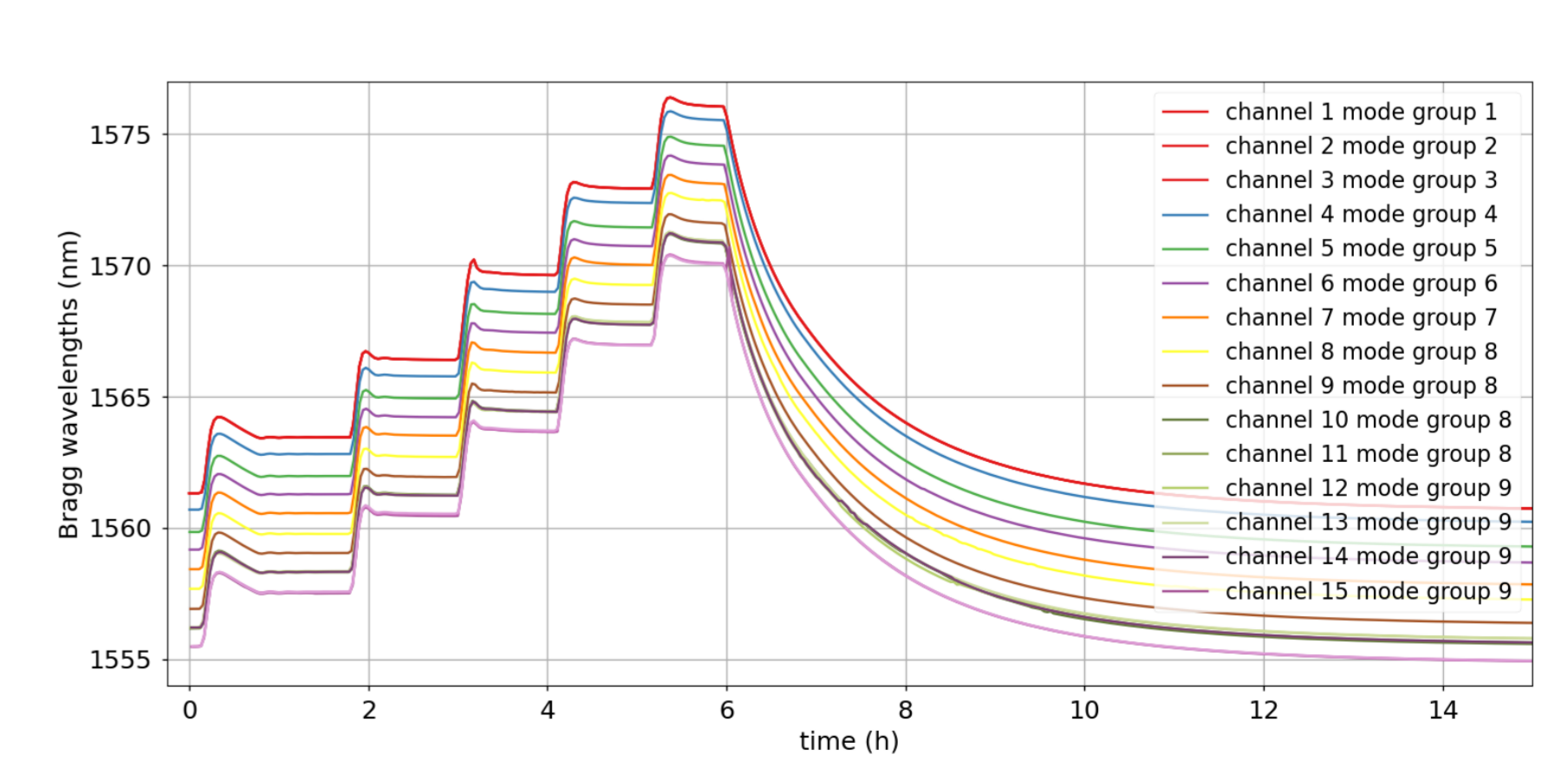
Here, we insert a FBG in a calibration oven programmed for five temperature steps (200-400-600-800-1000 °C) while 15 channels of the Proteus are interrogated using fiber optic switch. Fig. 6(a) depicts photographs of the instruments being used. Channels are selected in order to cover the nine groups of wavelength demultiplexed by 45-ch Proteus.



(a)



(b)



(c)

Fig 6. Photographs of experimental setup (a), examples of recorded spectra at six different temperatures for three channels (b) and recorded FBG wavelengths corresponding to the 15 interrogated channels (c) belonging to nine MGs.

Conclusion and perspectives

The ability of demultiplexing spatial modes in MMFs is of great potential interest for sensing applications since accurate filtering of the modal content of FBG reflected signals may allow for exploiting their different 2-D spatial profiles in core and cladding. Moreover, current development efforts taking advantage of specific materials for optical fiber and coating, as well as, adaptations of FBG inscription bench for HT MM sensor inscription, may also benefit from custom Proteus design adjusted to specific fibers, including adapted mode decomposition basis and number of channels.