



Fast Gated Superconducting Nanowire Camera for Multi-Functional Optical Tomograph

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D4.3: Optical Network Configuration

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About fastMOT

Traditionally, the monitoring of organs and deep body functional imaging is done by ultrasound, X-Rays (incl. CT), PET or MRI. These techniques only allow for very limited measurements of functionality, usually combined with exogenous and radioactive agents. In this project we are developing an innovative light sensing solution, a fast gated, ultra-high quantum efficiency single-photon sensor, to enable multi-functional deep body imaging with diffuse optics.

The new type of sensor is based on superconducting nanowire single-photon detectors that have shown to be ultra-fast and highly efficient. However, until now the active area and number of pixels has been limited to micrometres diameter and tens of pixels. We are using a combination of new techniques to overcome this limit and scale to 10,000 pixels and millimetre diameter.

In addition, we are developing new strategies for performing TD-NIRS and TD-SCOS to use this new light sensor optimally with Monte-Carlo simulations. We will implement the new light sensor in an optical tomograph and achieve a 100x improvement of SNR compared to using existing light sensors. With our Multifunctional Optical Tomograph we will be able to image deep organ and optical structures and monitor functions including oxygenation, hemodynamics, perfusion and metabolism.

Executive summary

In this deliverable we present an analysis of different alternatives in designing the optical network configuration together with the final choice. The optical network is composed of four sections: tomographic probe, light delivery, light collection and fiber-detector light coupling. For each section two or three alternative design choices are highlighted, including different numbers of fibers, different types of optical switches, the use of dichroic mirrors or a microlens array. Some choices are determined by research that has been published after the start of the project so their findings are discussed. Advantages and disadvantages of each option are compared including power, number of measurement sequence steps, area of analysis and technical challenges in implementing a solution. After all the considerations are explained and compared, a final optical network configuration is chosen, highlighting all its advantages and potential issues.

Abbreviations

Abbreviation	Definition
NIRS	Near Infrared Spectroscopy
SCOS	Speckle Contrast Optical Spectroscopy
SNSPD	Superconducting Nanowire Single-Photon
TD-NIRS	Time-Domain Near Infrared Spectroscopy
TD-SCOS	Time Domain Speckle Contrast Optical Spectroscopy

List of contributors

Institution	Name
CUSBO	Tommaso Palo <tommaso.palo@polimi.it>
CUSBO	Laura Di Sieno <laura.disieno@polimi.it>
CUSBO	Antonio Pifferi <antonio.pifferi@polimi.it>

CUSBO	Alberto Dalla Mora <alberto.dallamora@polimi.it>
ICFO	Lisa Kobayashi Frisk <lisa.kobayashi@icfo.eu>
ICFO	Turgut Durduran <turgut.durduran@icfo.eu>

1 Introduction and objectives

The objective of this deliverable is to report the best feasible strategies for TD-SCOS and TD-NIRS light delivery and collection. In each of the following four sections (Tomographic approaches, Light delivery to the probe, Light collection from the probe and Coupling of collection fiber to detector) a different part of the overall optical network is analysed. The analysis consists of dissecting multiple alternative solutions, comparing them, taking into account recent results in the literature and carrying out simulations. After various options are considered and described for each section, a final optical network configuration (applicable to the final prototype of Multifunctional Optical Tomograph) is described in the last section of this document, explaining why it was chosen. We note that the characterization and testing activities continue according to the initial plan, and this will be an iterative process with actions taken as new findings emerge from phantom and *in vivo* studies.

2 Tomographic approaches

The objective of fastMOT is to develop a tomograph with the ability to evaluate biological data in the x, y and z directions (with a single measurement) thanks to a combination of different source-detection pairs and by gating the photons at different arrival times. The structure of the tomographic probe needs to be a balance of several factors, including surface area analysed, measurement sequence duration, light collection efficiency and system complexity. Generally, the source-detector separation should not vary too much (total fluence increases by more than a decade per centimetre in most tissues of interest) between designs, as a short distance would increase the number of late photons but also disproportionately increase the number of early photons, blinding the detectors. However, we do note that one of the goals of the project is to implement time-gating to overcome this issue of saturation of the detectors and counting electronics, this will be done in parallel to the activities described here. A long distance instead would give too little signal even though allowing a higher depth sensitivity, so the optimal separation is decided to be a balance between these two

factors and is commonly in the range of 1-3 cm for standard sources/detectors [1][2][3]. We plan to break their limitations in fastMOT so this source-detector separation is not final. Another important note is that the detector is made of an array of detection pixels. Using more pixels to detect the light coming from a fiber will give a higher quality image for TD-NIRS, but, on the other hand, SCOS has to rely on individual, independent pixels and their number should be high. This is relevant for the tomographic layouts which include multiple collection points such as the linear and web layouts as there is an option to image all the collection fibers simultaneously. That means projecting each fiber onto a subsection of the total detection array, giving multiple images simultaneously but with the drawback of them being lower quality.

2.1 Octagonal layout

The octagonal tomographic layout is a simple single collection fiber layout with 8 injection fibers surrounding it as it can be seen in Figure 1A [3]. All source detector combinations in this layout are separated by exactly the same distance, providing a homogeneous study of the tissue surrounding the injection spot. The octagonal layout intended for fastMOT requires only a single detection fiber, meaning that the light collection design can be minimal (i.e. no requirement for an optical fiber switch or a fiber bundle). The injection fibers cannot all operate in parallel: if they did the collected data could not be assigned to a specific area of the mapped tissue. This will require an optical switch in the light delivery section, and a measurement sequence made of 8 steps. Also, as a note this layout (with the opposite configuration, e.g., 8 detections points and one single wavelength injection point) has already been used successfully for tomographic reconstruction, even if some artifacts due to the symmetrical configuration arose [3].

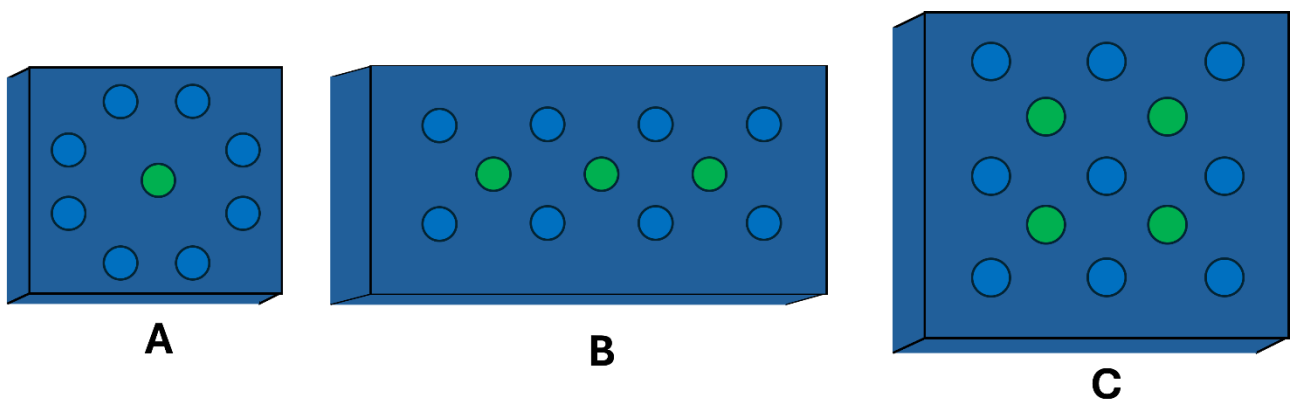


Figure 1. A schematic showing three alternative probe layouts described in this section. They are A: the octagonal layout, B: the linear stripe layout and C: the web layout. The blue dots represent the injection fiber sites, the green dots represent the collection fiber sites

2.2 Linear stripe layout

The linear stripe layout has 3 outputs and 8 inputs as can be seen in Figure 1B. The area covered is more rectangular than the octagonal layout, but all the different source detector pairs have very different separations, the largest being roughly 3.6 times greater than the smallest distance. This can be an issue in terms of getting too little signal in the source-detection pairs that are further apart. This layout requires multiple outputs meaning the light collection design will be more complex, requiring either a bundle of three fibers (each directed at a subsection the detector area) or an optical switch (3 x 1). In both cases there will be a longer measurement time required to either accommodate for the optical switching or to compensate for the lower number of detector pixels per fiber with the fiber bundle. Similarly to the octagonal layout, the 8 injection fibers will have to operate sequentially to differentiate the data describing the different areas of the mapped tissue, requiring an optical switch in the light delivery section and a measurement sequence made of 8 steps. The overall measurement sequence will be made of 3 steps for the collection and 8 steps for the injection giving a total of 24 steps. It is important to note that many of these steps will have lower-than-optimal photon count rates: 4 combinations will give very low counts (with source detection distance of 3.6 times the lowest distance), 8 combinations will give low counts (2.2 times the lowest distance) and finally the 12 remaining combinations will give the optimal counts at the lowest source-detector distance.

2.3 Web layout

The web layout has 4 outputs and 9 inputs as can be seen in Figure 1C. The area covered is greater than both the octagonal and the linear stripe layout. Once again there is variation in source detector separations when looking at different pairs of injection site and collection site (the largest distance being 3 times larger than the smallest) causing issues in optimising light intensity for the various pairs. Similarly to the linear layout, the multiple collection fibers will require either a 4x1 optical switch or a fiber bundle of 4 for the collection optical network. For the delivery optical network the requirement is still to have an optical switch, this time 1x9. The overall measurement sequence will be made of 4 steps for collection and 9 steps for injection giving a total of 36 steps. There will be different source detector distances, in detail there will be: 16 optimal distance pairs, 16 low countrate pairs at a distance of 2.2 times the lowest distance, and the remaining 4 at very low count rates with a distance of 3 times the lowest distance.

3 Light delivery to the probe

The fastMOT prototype will be made of two laser sources operating at different wavelengths and

pulse durations. Both are necessary for TD-NIRS and so an optical system design is required to deliver light from these sources by taking into account measurement sequence time, system complexity and consistency in attributing a detected photon to its original laser source. The following section will assume a tomography system with 8 injection sites, the arguments would not change for the 9 injection site web layout.

3.1 Interleaved pulses with 1x8 optical switch

The 1x8 optical switch layout relies on injecting the laser beams of the two light sources into the same optical fiber which then enters the 1x8 optical switch as can be seen in Figure 2A. To this end, one of the laser beams (fiber coupled) will be collimated to travel in free-space, transmitting through a dichroic mirror and then focused into a multimode fiber. The other beam will go through a different collimator and travel in free-space, reflect off the dichroic mirror and focus inside the same multimode fiber as the first beam. Since the two wavelengths will be substantially different, there will not be an issue in finding a suitable dichroic mirror to achieve a low-loss reflection for one wavelength and transmission for the other. This solution requires stable alignment of all the optical elements and accurate synchronization of the laser pulses. When travelling through the same fiber it is important that the pulses from the first laser source (Manny, Irsiome Solutions, France) do not overlap with the pulses from the second source and that the two are consistently distinguishable from each other. Furthermore, because of the collimation in free space there is more sensitivity to vibrations or instabilities compared to the second solution, that will be presented in the following section.

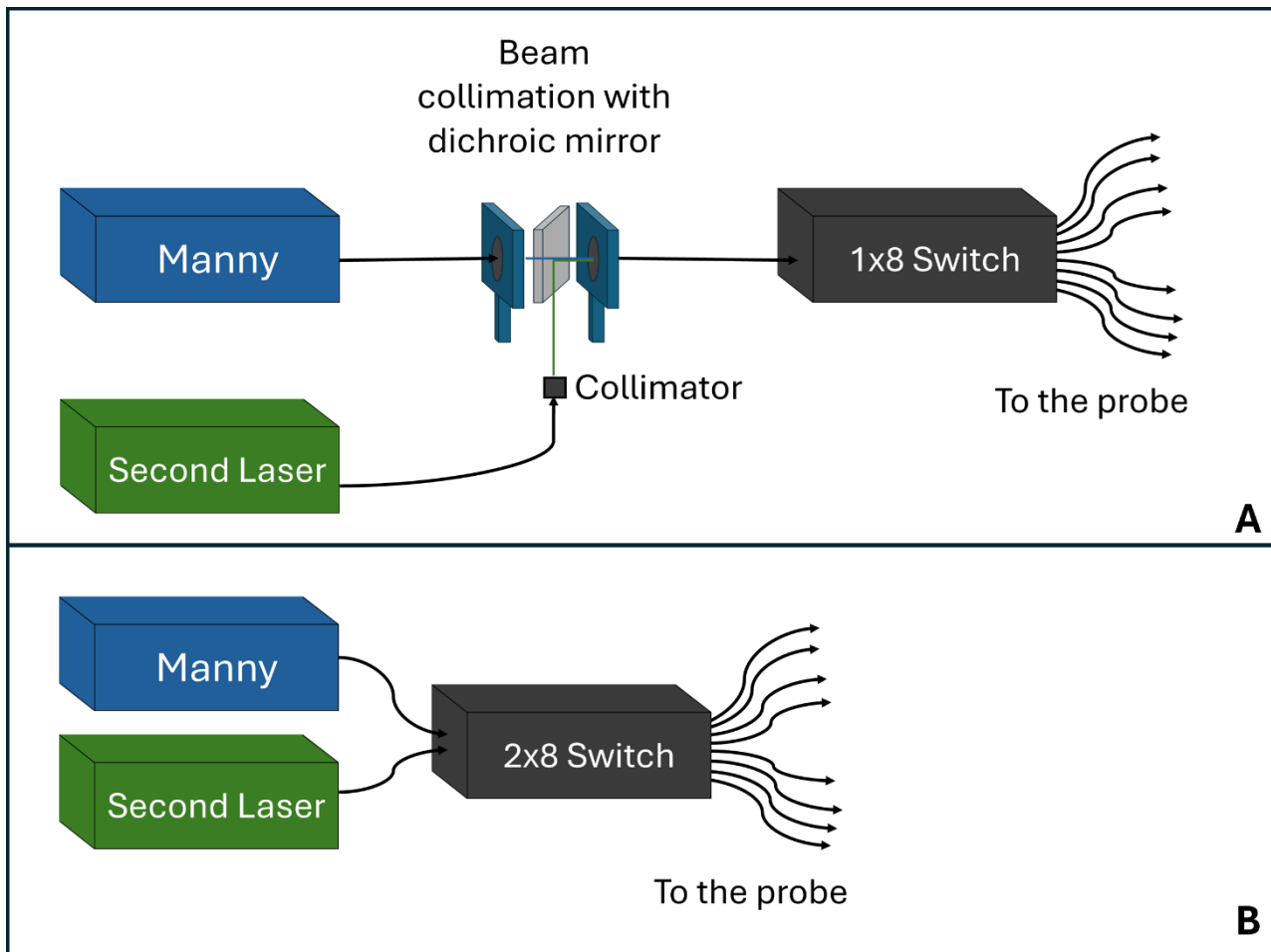


Figure 2. A schematic showing two alternative light delivery schemes described in this section. They are A: the interleaved pulses with a 1x8 switch and simultaneous operation and B: the alternating operation with a 2x8 optical switch. The dichroic mirror between the collimators present in the 1x8 scheme serves the function of uniting the beamlines of the two lasers into a single optical fiber. The arrangement of the first laser source transmitting and the second laser reflecting can be swapped around.

3.2 Alternating operation with 2x8 optical switch

The 2x8 optical switch system is considerably simpler to implement as can be seen in Figure 2B. It has a few flaws however when compared to the 1x8 system. The first issue is the number of steps in the measurement sequence which increases by a factor of two. This requires a longer measurement duration but also introduces more switching time during which there is no light delivered to the probe. The second issue is the power reduction, as can be seen in the calculation below. This issue can be partly addressed by operating the first laser in “burst mode”, allowing it to be off when the second source is connected and then back on with twice the power when it is connected [4].

The calculation for the average power during the measurement is as follows: define the

measurement duration as T_0 , the power output of the first laser as P_1 and the power output of the second laser as P_2 . Assuming a perfect and instantaneous optical switching, the first laser sends light for half the time, so $T_0/2$. The first laser also has a burst option which, if synchronized perfectly with the optical switch, can be made to operate at twice the power when it is sending light and at zero power when it is not. This means that during the time $T_0/2$ it operates at $2 P_1$. So the total energy delivered by the first laser is $T_0 * P_1$. The second laser instead still sends light only for a time of $T_0/2$, but without the possibility to double the power with its burst option, it operates at P_2 . So the total energy delivered by it is $\frac{1}{2} T_0 * P_2$.

The energy delivered in T_0 with the 2x8 optical switch therefore is $T_0 * P_1 + \frac{1}{2} T_0 * P_2$.

This is compared to the 1x8 optical switch where the energy is $T_0 * P_1 + T_0 * P_2$.

It is clear that, even considering perfect synchronization and instant switching there will be reduced overall power in this optical switching configuration, however, in this system there are no vibrational or instability issues as there are in the 1x8 optical switch configuration (reported before).

4 Light collection from the probe

The light collection network from the probe to the detector is strictly linked to both the probe design and detector coupling design and determines how the light speckle, formed by the analysed tissue, is transported to the detector. This step has crucial implications for the quality of the collected data. Both NIRS and SCOS benefit from a large number of detected photons, but while NIRS simply benefits from more light (benefitting from longer exposition times and larger detector area), SCOS in particular requires an image of the speckle to analyse the associated statistics (benefitting mostly from a large number of pixels employed in acquiring the image).

Very recently, some studies have shown that multimode fibers can be used efficiently to transport speckle data [5][6]. In particular the best fibers to use are graded-index multimode fibers [7][8]. Considering the signal-to-noise ratio of the measurement, it is therefore obvious to pick a multimode fiber over a single mode fiber due to the greater collection area of the former. There are still different ways to arrange multimode fibres, each with their advantages and disadvantages. A schematic of these layouts can be seen in Figure 3.

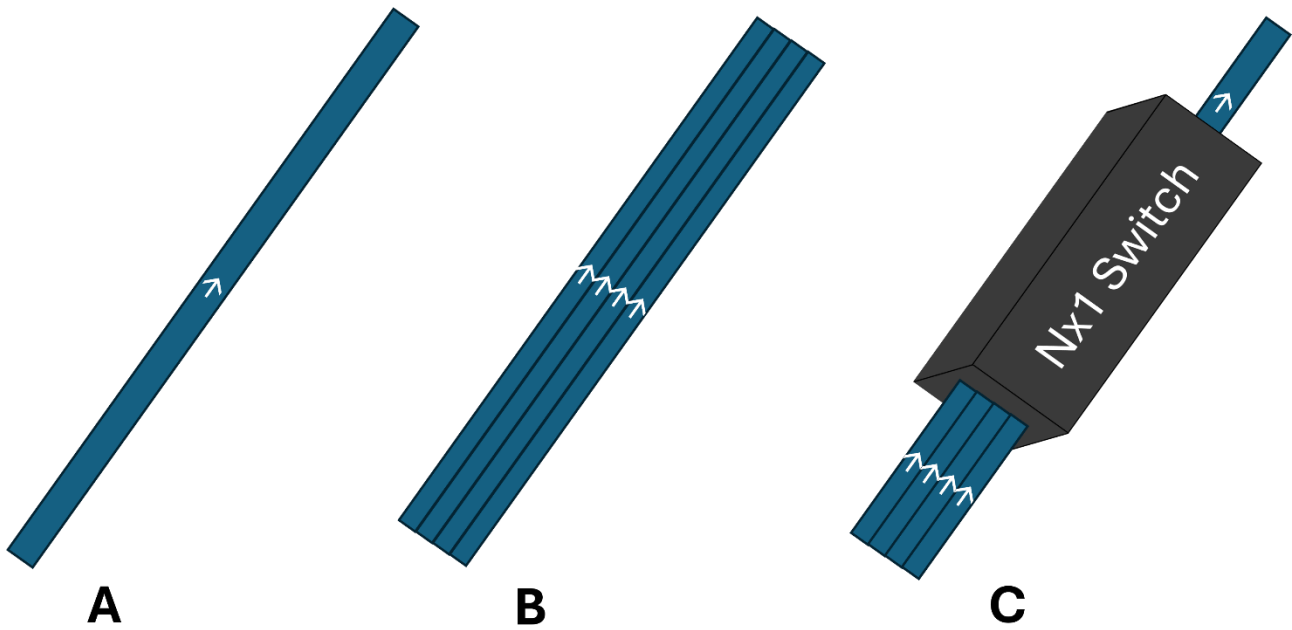


Figure 3. This schematic shows three alternative schemes for light collection from the probe and delivery to the detector. In A a multimode fiber is used, in particular for the octagonal probe layout. In B a bundle of multimode fibers transports speckles for the various collection spots of the multi-output probe directly to the detector. In C the bundle of multimode fibers is connected to an optical switch which analyses one collection spot at a time.

4.1 Single fiber

A multimode fiber is the best option for a single collection fiber probe like the octagonal probe. The alternatives would be a multimode fiber bundle to increase the collected light (though it does not straightforwardly increase the detected light as there would be dead regions on the detector) or a single mode fiber to increase the speckle contrast (though with well-designed imaging setups single mode fiber stops outperforming the multimode fiber). The single mode fiber shows, arguably, an increase in beta [9], but it is not sufficient to account for the $\sim 300\times$ difference in collection area (which translates to higher countrates) compared to the multimode fiber. The bundle of multimode fibers instead runs into more practical issues such as difficulty in coupling well the fibers to the detector, as well as emitting light over a surface area greater than the detector active area, meaning the optics should shrink the image onto the detector and lose a lot of the potential contrast. Another issue of the multimode fiber bundle is the inhomogeneity between the fibers, which can be accounted for with speckle defocusing or correction algorithms[10][11].

4.2 Bundle of fibers

Using a bundle of fibers is a good solution for light collection from probes with multiple outputs like the linear or web layouts which have 8 or 9 collection sites. Each one of them is connected to a

multimode fiber which transports the speckles to the detector in parallel with the other fibers. This solution is simple for light collection to the detector but generates more complexity in coupling to it, where the various fiber cores have to be focused on the detection array. There is a reduction in the number of steps for the measurement sequence as each collection site is analysed simultaneously. However, this means that the data from a single collection site is being detected only by a fraction of the total available pixels, leading to a potentially lower precision and accuracy for SCOS. Another downside might be that the arrangement of the circular fiber cores on a square detector array might leave some gaps and dark spots in the detector, lowering the maximum countrate.

4.3 Multiple fibers with Nx1 switch

A good alternative to using a bundle of fibers for the multiple outputs probe layouts is the use of an Nx1 optical switch. Each collection site is connected to a multimode fiber which transports the speckles to the optical switch. The switch then couples the collection fibers to the detector in series, only observing one collection site at a time. This solution is slightly more complex in the section from the probe to the detector due to the extra optical element inserted but does not require any further complexity in coupling the light to the detector. There is an increased number of steps in the measurement sequence by a factor of N as each collection site has to take its turn in being observed and there is also some time that is wasted waiting for the optical switch to settle. However, each site is detected by the whole detector array, yielding higher quality data. Also, the optical switch does not disrupt the speckle statistics. Studies have shown that the impact is minimal, if not non-existent [12].

5 Coupling of collection fiber to detector

The final part of the optical network design is the coupling of detected light to the detection array of superconducting nanowire single photon detectors produced by Single Quantum, Netherlands. The light travelling through the optical fibers will be projected onto a pair of lenses which will first collimate the beam and then focus it onto the detector, as can be seen in Figure 4A.

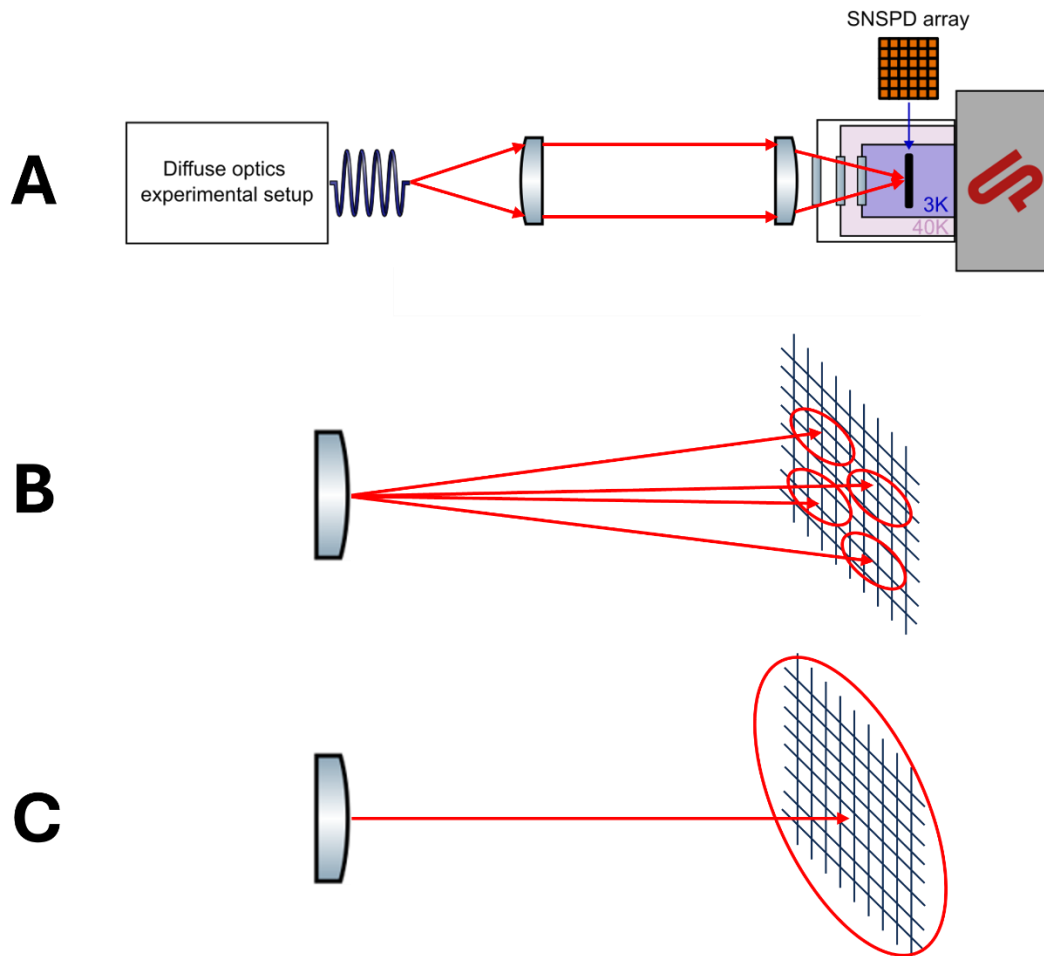


Figure 4. Schematic showing the optical network configuration for the coupling of light to the detection array. A: The overall schematic. B: The multiple fiber projection design to image N collection spots simultaneously. C: The unique multimode fiber imaging design for one collection spot at a time.

5.1 Multiple fiber projection

The multiple fiber projection is a requirement if a bundle of multimode fibers is used for light collection. This has all the advantages of the bundle of multimode fibers: reduced number of steps in the measurement sequence and lower number of pixels per fiber. It also has all the disadvantages: potentially lower illumination area of the detector and need for accounting the inhomogeneity of the various fibers. This smaller illuminated area, as can be seen in Figure 4B, can be estimated to be a factor of 0.9 to 0.8 of the illuminated area for Figure 4C. Another issue is the focusing of light onto the detector: if there is only one lens, there is a risk of creating optical aberrations reducing image and data quality as the image points cannot all lay on the optical plane. To fix this it is possible to implement a microlens array, one lens for each fiber, though alignment and implementation can be much more complicated.

5.2 Single fiber imaging

The single fiber imaging system is required for light collection choices such as the unique multimode fiber and the Nx1 optical switch. It is very simple and makes use of as much detector area as possible without any risks of assigning the data from a pixel to the wrong collection fiber. The only important design choices are the focal length and position of the lenses. We simulated on Zemax a setup with a lens pair as can be seen in Figure 5. Here the lenses are left: AC254-100-C-ML and right: AC254-250-C-ML, both from Thorlabs, USA.

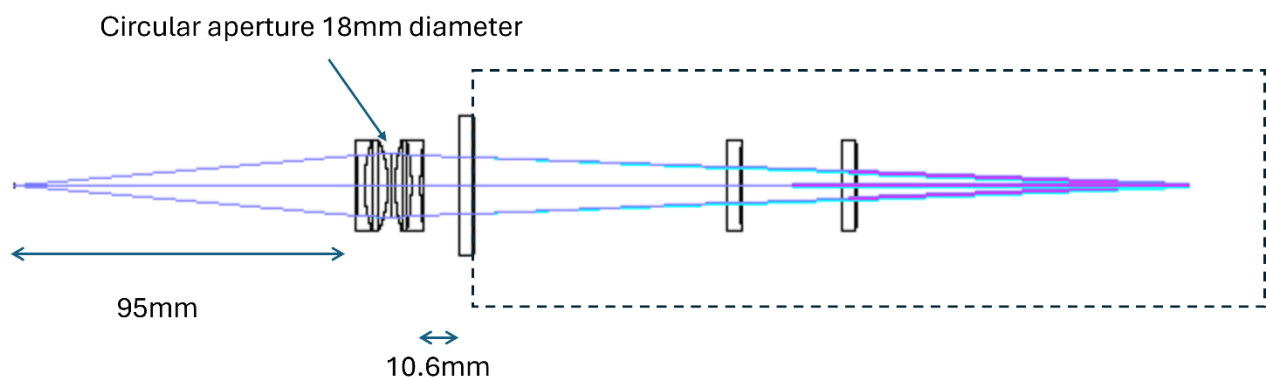
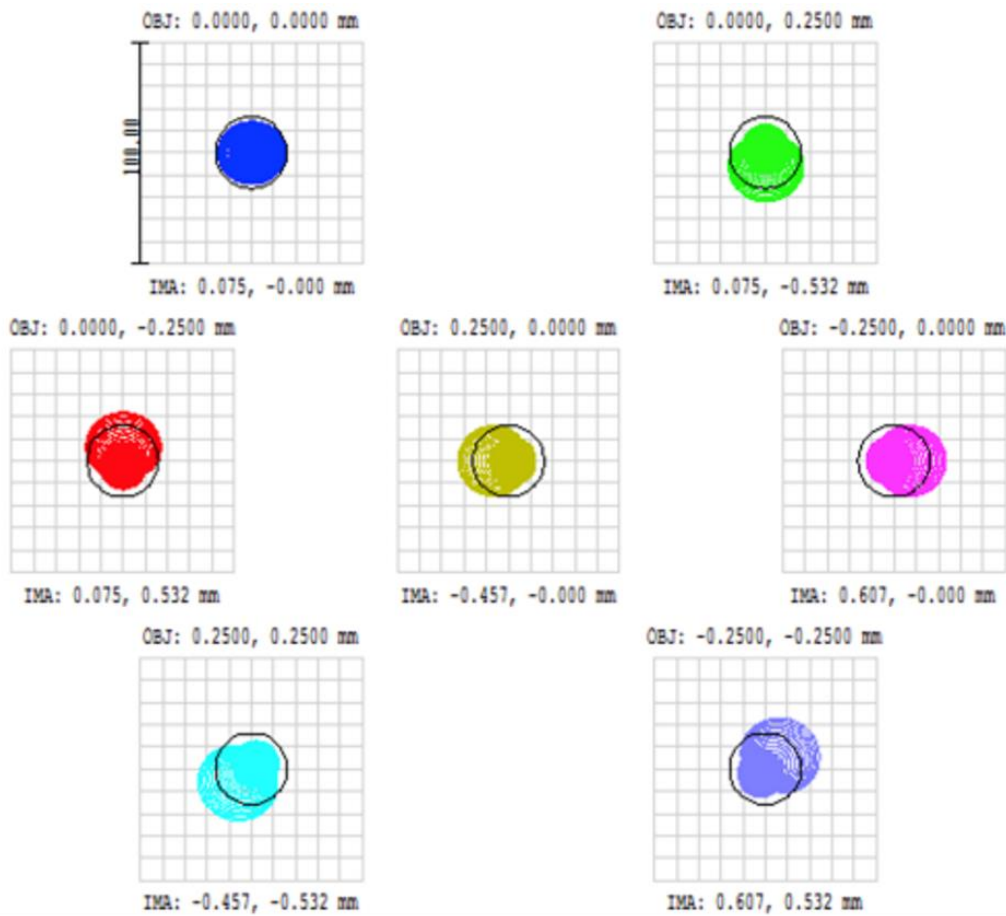


Figure 5. Representation of lens layout scheme for the single fiber imaging, from left (collection fiber tip) to the lens pair, to detector windows (inside dashed lines) to the right (plane of focus at detector array). Here the lenses are left: AC254-100-C-ML and right: AC254-250-C-ML, both from Thorlabs, USA.

The results of the simulation with the setup and a 1064 nm laser source can be seen in Figure 6, where the airy disc size and the displacement-induced aberrations are satisfactory. In general, this validation solidifies the single fiber imaging choice as a simple and effective solution for fiber-detector coupling.



Airy disc size ~16 microns

Figure 6. The result of a Zemax simulation for the optical system shown in Figure 5 and a laser source operating at 1064 nm. The produced spot diagrams show the image produced by the system when an object is displaced by 0.25 mm in different directions. The spots also show the dimension of the optical aberration, with displacements from the centre by small distances in the order of 0.5 mm (indicated by "IMA" below each spot diagram). Overall, the airy disc size is of roughly 16 μm , which is satisfactorily small. The optical aberrations are also satisfactorily small.

6 Final Configuration

After analysing the proposed alternative solutions, the optical network configuration of choice will be: an octagonal probe layout, receiving interleaved pulses with a 1x8 optical switch, and collecting light from a multimode fiber coupled to the detector with a lens doublet. The overall network can be seen in Figure 7. This decision comes from considering overall complexity and system function, where the simplest solutions were most often chosen over the complex ones except for the light delivery section (where our choice was to assemble a dual wavelength laser source). This is because the delivery of interleaved pulses offers important advantages such as higher power and reduced number of steps

for the measurement sequence. The other sections were chosen based on simplicity but also duty cycle extension and reduced number of optical elements (as every new element introduces potential losses). Having a 2x8 switch at the start, and then a light collection Nx1 switch would have given a rather large number of steps in the measurement sequence and a lot of switching dead time. This way instead the whole tomographic scan is carried out with only 8 switches, arguably the minimum required number. Besides the reduced number of steps in the measurement sequence, this network configuration provides higher power (thanks to the interleaved pulses, fewer optical elements), good count rates (due to the higher power and the better usage of the detection array), a clear speckle image (making full use of the detector area to image a single multimode fiber and reducing the impact of optical aberrations), and a smaller measured area (due to the smaller dimensions of the probe). Even though the measured area is smaller, that comes with the advantage of a faster acquisition: a smaller probe means fewer fibers and therefore less optical switches for one complete scan.

This design choice comes with flexibility for different applications: by rotating through the various injection spots with the optical switch it's possible to carry out measurements such as static tomography for lesion characterisation. If instead one keeps the switch stuck on one of the injection fibers then a couple different measurements become a possibility such as fast monitoring by quickly acquiring data for the same spot. Another one might be the scan of a larger surface area by physically moving the handheld probe over the surface area of interest, even in a non-contact manner.

With this network configuration implemented for the final prototype we will have in our facility in CUSBO a good multifunctional optical tomograph for deliverable 4.4.

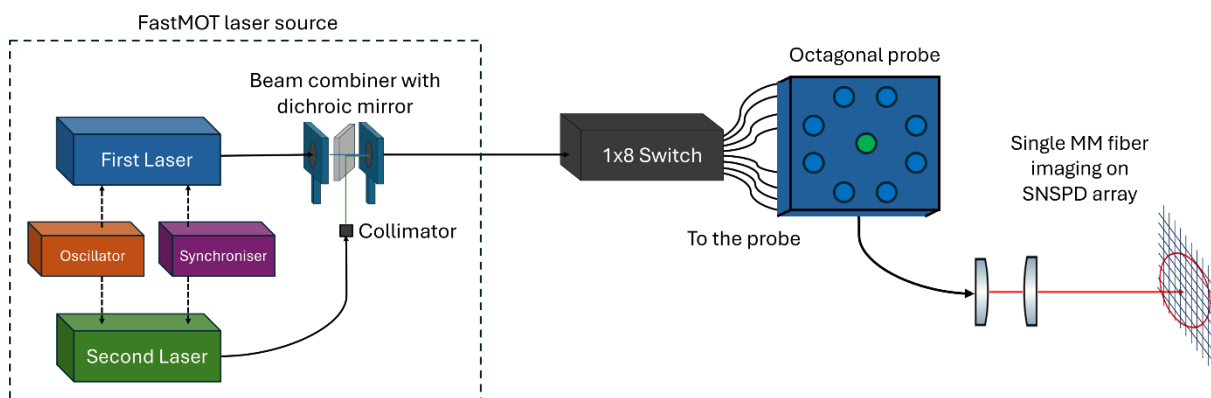


Figure 7. The overall optical network configuration of choice, based on analysis of the alternatives for each section. The network consists of a custom-made 2-wavelength laser source delivering interleaved pulses through a dichroic mirror setup, operating simultaneously thanks to an oscillator and a synchroniser, a 1x8 optical switch, an 8-input 1-output optical probe (with an octagonal layout), a multimode fiber, and a multimode fiber imaging system in front of the detector.

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