I. INTRODUCTION

By harnessing intrinsic light-matter interactions, distributed fiber sensing methods enable off-the-shelf optical fibers to operate as highly sensitive sensor arrays. Multiple variations of these techniques have been used to measure a diverse range of physical parameters, from the acoustic and optical properties of the fiber’s surroundings to direct measurements of the interrogated fiber’s physical state (e.g., pressure, temperature, or axial strain). Distributed acoustic sensing (DAS) encapsulates the subset of distributed sensors oriented towards fast acquisition of the axial strain profile along a fiber cable, and has traditionally been seen as a way to expand the design of distributed sensing methods in areas such as surveillance, pipeline monitoring, and vertical seismic profiling.

Recently, DAS has captured the attention of the geophysics community for seismic studies, and considerable research efforts are now aimed at addressing the demands of this new application space. Despite its recent adoption, however, there are plenty of demonstrations of its successful use in geophysical settings: from metropolitan areas to near-shore deployments. Nonetheless, environments demanding access to the full extent of ultra-long-haul telecommunication links are still mostly inaccessible through these technologies, which are limited to 100 km ranges despite remarkable efforts at range extension.

The deep ocean floor is a particularly relevant example of an environment where traditional geophysical sensing equipment is sparse, costly, and often temporary, and where the existence of transoceanic telecommunication fibers presents an exceptional opportunity for fiber-based sensing. So far, attempts at exploring transoceanic fibers for sensing have remained limited in their localization capabilities, either unable to discriminate the origin of each strain contribution, or able to localize only a few dominant perturbations along the cable through bi-directional measurements. Fully distributed DAS techniques, on the other hand, struggle to meet the criteria for sensing in such long-haul cables. The reasons go beyond the aforementioned range limits, as their fundamental reliance on intrinsic backscattering for localization imposes a barrier to massive range enhancement via in-line amplification (owing to the presence of optical isolators in the amplifiers), and the probe pulse’s characteristically high peak powers render these techniques incompatible with co-propagating data channels, which is especially limiting given the lack of abundant fiber strands in transoceanic cables.

These fundamental roadblocks to ultra-long range DAS motivate the exploration of novel interrogation methods, capable of surpassing the fundamental challenges of current DAS techniques in specific settings. One possible way to expand the design of distributed sensing methods is to target future telecommunication fiber deployments. At the moment, the ability to transport data traffic is lagging under the ever increasing demands of consumers, limited by the gain band of in-line amplifiers and the available power budget of telecommunication fibers. The current techno-economic landscape suggests that the next iteration of telecommunication fibers will expand capacity through space-division multiplexing (SDM) techniques (either in the form of few-mode or multi-core fibers) in order to remain economically competitive. Transoceanic distributed sensing methods are expected to closely follow these developments, opening new opportunities to address existing technical limitations by exploring the new spatial degrees of freedom of a multimode telecommunications backbone.

Existing few-mode fiber sensing demonstrations have employed the added modes to tackle cross-
sensitivity [32], improve SNR [33], or in the case of multi-core fibers, mostly for complementary measurements using multiple independent channels [34]. One aspect that is less targeted is the need for bidirectional propagation in existing distributed sensing techniques: either for roundtrip time-of-flight measurements [10, 36], or to engineer a local parametric interaction between two counter-propagating lightwaves [35, 37].

Multimode platforms enable the generalization of the time-to-position mapping principles to co-propagating designs, provided that the carried modes/supermodes are weakly coupled and possess different group velocities. This mapping can be observed in reports on the characterization of multimode links and devices [38, 39], as well as a recent sensing work which proposed the measurement of changes in the local coupling strength as a way to monitor the distribution of transverse stresses applied to the fiber [3]. Yet, more relevant sensing quantities such as strain/temperature remain unexplored, and no sensing demonstration to our knowledge has relied on the baseline coupling and intermode/intercore crosstalk for interrogation - instead, it has been considered as one of the main drawbacks of few-mode fibers (FMF) for sensing purposes [29].

In this work, we demonstrate a method for coherent, distributed interrogation of the fiber in transmission, via swept-wavelength interferometry [10, 32], able of measuring common distributed sensing quantities such as strain and temperature. Our technique avoids common drawbacks such as the range limitations originating from the coherence length of widely tunable sources, and the need for a dedicated, optical path-length-matched, local oscillator fiber for recovery of the fiber transmission response. We expect this work to spearhead future unidirectional, multimode distributed sensing designs, able to benefit from in-line amplification and easily integrable with future data-carrying, ultra-long haul telecommunication links, thus unlocking dense (kilometer-long resolutions) strain and temperature sensing in future transoceanic (and other ultra-long-haul), amplified fiber deployments.

II. SENSING CONCEPT

Our transmission-only sensing method is illustrated in figure 1. A short pulse of light is injected into the fundamental mode (OAM<sub>0</sub>, in the Optical Angular Momentum mode basis [43]) of a two-mode fiber. Under the assumption of constant weak coupling between mode groups, while most light remains in the same mode as it was injected, a small fraction is coupled to one of two degenerate higher-order modes (OAM<sub>±1</sub>) over every position in the fiber. Our assumption of weak coupling is valid for the purposes of telecommunication few-mode operation, and constant coupling can be assumed for our perturbations of interest (axial strain/temperature) for a two-mode fiber [44].

After coupling, the now higher-order mode light experiences both a different propagation constant, β<sup>(0)</sup>, and a different group velocity, v<sup>(0)</sup> (λ being the topological charge of the corresponding OAM mode) for the remaining length of fiber. The difference in each of these two quantities enables the estimation of measurand amplitude and localization of perturbations along the fiber link (see figure 1).

Localization information is encoded in time as a result of the difference in group velocities between mode groups, since light coupled from the fundamental mode at each position will be displaced from pre-existing light in the higher order modes. As a result, at the fiber output, the OAM<sub>±1</sub> signal will display a broad temporal envelope, each time instant mapping to a specific position in the fiber.

The position information can therefore be recovered via a differential time-of-flight measurement on the higher order mode output. The observed temporal walk-off for light undergoing coupling at position z will be a function of the remaining length of fiber (L<sub>FUT</sub> − z) and the differential mode group delay (DGD = 1/v<sup>(±1)</sup> − 1/v<sup>(0)</sup>) between the two mode groups

\[
\Delta t(z) = DGD(L_{FUT} - z).
\]

This method of localization is analogous to the traditional backscattering-based methods in conventional distributed techniques, which rely on roundtrip time-of-flight for position discrimination. The differential nature of the measure, however, yields a temporally compressed optical trace (i.e., the impulse response obtained for a given pair of input/output modes) compared to traditional roundtrip measurements (by a factor \(CF \approx -\frac{2\pi}{\Delta t(0)}\)). The justification and the implications of this compression are described in detail in the supplementary section 1.

Any perturbation to the local optical path of the fiber (induced by strain or temperature, in this case) can be measured by comparison of the recovered optical trace to a previous acquisition. This is achieved by an interferometric measurement of optical path length difference, similar to Rayleigh scattering based systems [10, 36]. As light couples from the OAM<sub>0</sub> mode to any of the higher order OAM<sub>±1</sub> modes, it shall interfere with pre-existing light in the higher order mode with which it overlaps. The optical path difference accumulated due to propagation as different modes over any length of fiber enables us to perceive the fiber as a stack of effective interferometers (sensing points), which we are able to individually access via the aforementioned ability to pinpoint the origin of the coupling by a time-of-flight measurement. The resulting noise-like output of the higher order mode (the optical trace), stores the response of each of the sensing points of the fiber at different time instants.

Recovering the measurand information can then be achieved in one of two ways: by observing the changes to the instantaneous phase evolution along the obtained
higher order mode output (analogous to coherent phase-sensitive OTDR interrogation [45], or by probing the equivalent frequency shift that compensates the change in the intermodal interference due to a perturbation-induced change in local optical path difference (in analogy to frequency-demodulation phase-sensitive OTDR methods [46, 47]). We opt for the latter approach, since it avoids problems resulting from cumulative measurements of phase, such as poor phase estimation at points of fading and ambiguity due to phase unwrapping errors.

Consider the interference happening at position \( z \) in the fiber, as newly coupled light interferes after travelling a short length \( dz \) (stored at a specific time-instant of the recovered optical trace, given by equation 1). The phase difference accumulated between the two interfering waves due to the difference in propagation constants will be \( \Delta \varphi(z) = \Delta \beta dz \) (for \( \Delta \beta = \beta^{(0)} - \beta^{(=1)} \)), which may be re-written as

\[
\Delta \varphi(z) = \frac{2\pi}{c_0} (\Delta n(z) \cdot dz) \nu_0.
\]  

Equation 2 illustrates the equivalence of altering the optical path difference \( (\Delta n(z) \cdot dz) \) \( (\Delta n = n^{(0)} - n^{(1)} \), \( n^{(0)} \) being the effective index of each respective mode of \( \ell \) topological charge) and detuning the probe center frequency \( \nu_0 \) by a specific amount. A change in the optical path difference \( (\Delta (\Delta n(z) \cdot dz)) \) can therefore be adequately compensated by a change in center frequency, such that

\[
\frac{\Delta \nu_0}{\nu_0} = \frac{\Delta (\Delta n(z) \cdot dz)}{(\Delta n(z) \cdot dz)}.
\]  

A simple strategy for interrogation of all sensing points, then, consists of probing the FUT with multiple center frequencies and reconstructing the frequency response of each effective interferometer formed at every position in the fiber. A perceived shift in the frequency response will therefore be proportional to the optical path difference, according to the relation given in equation 3. Strain and temperature can then be inferred from well known fiber coefficients that take into account the total length change, elasto-optic effect, thermal expansion and thermo-optic effect [47].

### III. EXPERIMENTAL DEMONSTRATION

To experimentally demonstrate our proposed method, we slightly depart from our previous simplified conceptual description. The main difference is the use of a continuous-wave frequency swept input instead of a pulse for interrogation. This type of interrogation is commonly seen in other distributed sensing schemes [36], and generally enables much improved spatial resolutions compared to time-domain (pulsed) implementations. We note that high resolution swept-wavelength interferometry (SWI) techniques in backscattering methods are known to struggle in probing long lengths of fiber due to the limited coherence length of available sources [48]. This trade-off is massively relaxed in our design by having the local oscillator (OAM\(_0\) output) and measurement path (OAM\(_{\pm 1}\) output) travel through the same fiber, being therefore automatically optical path-length-matched.

The use of a frequency-domain interrogation method is important for two main reasons: first, it facilitates the use of the ballistic OAM\(_0\) output as the local oscillator, since the self-heterodyne and time-to-frequency mapping nature of the measurement enables the local oscillator to be conveniently spectrally separated (upconverted in the frequency domain) from the measurement outputs by the simple introduction of a fiber delay; and second, the improved spatial resolution from SWI facilitates the demonstration of proof-of-principle in a benchtop experiment, using standard commercial fibers. This is particularly relevant considering the intrinsic penalty to spatial resolution by our proposed technique versus backscattering methods.
The maximum achievable spatial resolution in our methodology $\zeta_{\text{max}}$ is proportional to the total bandwidth spanned by the sweep and the DGD, $\zeta_{\text{max}} \propto \frac{1}{B_{\text{max}} \cdot \text{DGD}}$. In our specific implementation, however, each acquired sweep is divided in several sub-sweeps of bandwidth $B_{\text{sub}} < B_{\text{max}}$, each with a different laser center frequency $\nu_0$. This is the second main difference from the previous conceptual description, and it enables us to reconstruct the frequency response of the fiber from a single swept acquisition, simultaneously probing the fiber with multiple center frequencies at the cost of spatial resolution.

As a result, the calculated spatial resolution $\zeta$ is given by

$$\zeta = \frac{1}{B_{\text{sub}} \cdot \text{DGD}},$$

and can be determined in post-processing by choosing the number of independent sub-sweeps (or the total bandwidth of each sub-sweep) that the acquired portion of the scan is sliced into. This interrogation method entails a inverse proportionality between the sensor’s measurand resolution, spatial resolution and total bandwidth $B_{\text{max}}$, due to the limits of estimation accuracy of the frequency detuning $[49]$ (a discussion of these trade-offs is provided in the supplementary section 3).

Successfully employing SWI with a broadly tunable laser source also demands several post-processing steps, in order to correct non-linearities of the laser sweep and address the variation in sweep rates over acquisitions. Both of our sensing demonstrations used a FUT consisting of a single 2300 meter long step-index SMF-28 fiber (carrying 2 mode groups at 1064 nm). The FUT configurations used in each experiment are represented in figure 2.

**FIG. 2.** a. Simplified depiction of the interrogation setup. The complete setup is described in the methods section (figure 3). b. Recovered impulse response obtained from one sub-sweep, for a single mode and polarization using swept-wavelength interferometry. Amplitude is normalized to the initial peak at time delay 0, occurring from poor demultiplexing at the output (see supplementary section 2 for additional information on the optical traces). c. FUT configuration for the single-point strain measurement and d. for the multipoint temperature measurement.

The multipoint Temperature Measurements

To first evaluate the potential for distributed sensing and validate the principle for localization and discrimination of multiple measurements within the fiber, we performed a multipoint sensing measurement by heating two positions in the fiber. We generated two hotspots by coiling two sections of fiber (~10 m long and ~15 m long) separated by more than one spatial resolution (figure 2). Room temperature was measured to be approximately 22 °C.

Each of the fiber coils were heated by hovering a warm object (~35 °C) close to the coils for about 1 minute without touching the fiber, and then removing it and allowing that hot spot to cool down. The spatial resolution was calculated to be 16.1 m according to equation 4 (see the supplementary section 2 for details in the determination of fiber DGD and laser sweep rate).

The results are depicted in figure 3. The spatial separation between both perturbations is clearly evidenced by computing the RMS temperature shift in the dashed areas, and plotting them in the bottom part of the figure. Notably, we see that the full-width at half maximum for the perturbation observed for the influence is 22.78 m for the ~10 m long hot spot and 23.65 for the ~15 m long one. These results are reasonably consistent with the estimated lengths for the coils and the calculated spatial resolutions. Nonetheless, they seem to suggest some worsening of spatial resolution, which is expected to occur due to fluctuations in the laser sweep rate over each acquisition (see supplementary section 2).

The temperature is calculated from the apparent effective frequency shift using standard coefficients used for telecommunication step-index fibers [24]

$$\Delta T \approx \frac{1}{6.92 \times 10^{-6}} \frac{\Delta \nu_0}{\nu_0}.$$

We notice the appearance of some residual crosstalk between spatial channels at positions prior to the measurement. While crosstalk effects have been observed for other Rayleigh-based distributed sensing methods, there are clear distinctions when compared to our approach. First, spatial crosstalk normally affects subsequent positions in backscattering-based technologies, and can be
calculated from the amplitude of the perturbation that induces it [50]. This is contrasted with what we observe in the transmission setup: the crosstalk affects positions prior to the point of perturbation, and does not seem to scale predictably with the perturbation that induces it. This suggests that the origin might be an indirect effect, onset by changes to the strong coupling between the two degenerate OAM \( \pm 1 \) modes. One possible explanation in this case may be a change in coupling strength from a combination of the fiber coiling and thermal effects. This is supported by the fact that the shorter coil had approximately half of the coiling radius as the longer coil (leading to stronger crosstalk). This may not occur in fiber installations that are not substantially bent or coiled, and may be avoided altogether through the use of a nondegenerate higher order mode for interrogation (thus avoiding any strong coupling effects), in fibers carrying a higher number of modes.

Strain Measurements

To evaluate the potential for strain measurements and assess the linearity of our interrogation process, we coiled a roughly 15 m long section of the fiber around a piezoelectric cylinder, at meter 500. A slow sinusoidal oscillation with 100 s period was applied to the fiber stretcher, with 100 V amplitude (\( \sim 100 \, \text{n}\varepsilon/V \), according to specifications). The strain distribution was recovered over 300 seconds, and is represented in figure 4. The acquired effective frequency shift was converted to strain through the following relation [47]:

\[
\varepsilon \approx -\frac{1}{0.78} \frac{\Delta \nu_0}{\nu_0}
\]  

Once again, the spatial resolution was selected to be 16.1 m, which was found to maximize the strain SNR for the recovered perturbation. The amplitude of the measured strain sine wave was found to be 16.4 \( \mu \varepsilon \), and the strain resolution (computed as the average of the standard deviations of all points in an undisturbed section of fiber, from meter 700 to 1600) was measured as 1.2 \( \mu \varepsilon \).

![FIG. 3. Multipoint temperature measurement. a. The full fiber temperature profile. b. Close up of the perturbation region. Dashed regions mark sections to calculate the root-mean-square temperature shift to observe the spatial resolution (bottom subplot). Right subplot shows the temperature measurement at the point of highest perturbation amplitude for each hotspot over time.](image1)

![FIG. 4. Strain measurement. a. The full fiber strain profile. b. Close up of the perturbation region. The subplot shows the strain signal at PZT section of fiber (blue) and of an undisturbed position in the fiber (red), for comparison. Green shows the waveform applied to the piezoelectric fiber stretcher.](image2)
Experimental Setup

The full schematic for our setup is depicted in figure 5. The laser source was a Toptica CTL 1050, operating at center wavelength 1064 nm and swept by driving the internal stepper motor with a 0.2 Hz sine wave. 10% of the laser output power is diverted into an unbalanced Mach-Zehnder interferometer (having 20 m delay fiber in one path), which is used to measure the laser sweep rate and to correct nonlinearity in the frequency sweep in post-processing (see supplementary section 2). The remaining 90% (∼ 12 dBm) are launched into the FUT. The fiber is swept at an average rate of 1.63 THz/s (6.19 nm/s) over each acquisition (consisting of 8.3 s around the point of highest linearity of the positive slope of the sinusoidal modulation).

The fiber under test consisted of 2.3 km of SMF-28 fiber carrying three modes (2 non-degenerate mode groups, OAM_0 and OAM_{±1}) at the probe wavelength. The DGD was measured to be 1.23 ps/m (see the supplementary section 2 for information on the measurement of DGD). At the input, light is injected exclusively into the OAM_0 mode. At the output, the three modes carried by the fiber are separated through a free-space spatial mode demultiplexer: the fiber output is collimated into free space and split into 3 paths. One of the paths is immediately coupled into a single-mode HI1060 fiber, without undergoing any mode conversion, while the other two are sent through spiral phase masks (which add/subtract 1 topological charge) before being coupled to the single-mode HI1060 fiber. The spiral phase masks function as a mode converter, while the single-mode fibers act as a spatial rejection filter that only accepts the portion of light with 0 topological charge. The OAM_0 output is then used as the local oscillator of a polarization diversity balanced detection scheme. The OAM_{±1}/OAM_{1} are delayed by approximately 10/20 meters of fiber (respectively), and then combined through a 50:50 fiber directional coupler.

The introduction of the 10/20 meter delays deliberately introduces a group delay to the whole optical trace of each individual mode, which upconverts the beatnote resulting from the interference with the OAM_0 oscillator, allowing us to spectrally separate each of the two optical traces with a single measurement [29, 40].

The perturbation for the strain experiment was accomplished by having approximately 15 m of fiber coiled around a piezoelectric cylinder, used as a fiber stretcher. The perturbation was a 100 V amplitude sine wave with 100 second period, with a 50 V offset in order to prestretch the fiber and prevent strain non-uniformities. The perturbation for the temperature measurements was achieved by hovering a warm object (∼ 35 °C) about 1 cm above the coiled fiber constituting the hotspot. At every acquisition, the signals are directly sent to a computer for storage and processing. The full processing stack is explained in detail in the supplementary materials, section 2.

IV. DISCUSSION

In this work, we introduced and demonstrated a new method to perform distributed sensing of common physical parameters by exploring the weak coupling between spatial modes carried in optical fibers, relying exclusively on unidirectional propagation in the fiber.

As a proof-of-concept, we performed two sensing demonstrations using standard step-index SMF-28 working in few-mode operation. We successfully localized and demonstrated linear measurements of strain/temperature with inferred measurand resolutions of 1.2 µε (0.135 K, in equivalent temperature), and spatial resolutions in the tens of meters, at acquisition rates of 0.2 Hz. While these values are not representative of the ultimate performance limits of the technique and there is ample room for optimization, they serve as strong evidence for the future potential of this sensing principle. In particular, optical SNR is limited by the imperfect correction of the laser sweep nonlinearity and imperfect spatial mode demultiplexing at the fiber output, and the acquisition rate is limited by the total time required to ensure an approximately linear sweep from the laser source. Also, despite the slow acquisition rates, we note that this type of interrogation in fact relaxes the fundamental acquisition rate limit of common backscattering implementations, which require the minimum of full roundtrip time for the whole length of interrogated fiber between acquisitions. Conversely, our method benefits from a much narrower recovered optical trace such that this condition is massively relaxed, and multiple probe pulses can simultaneously coexist in the same FUT.

We also highlight the important distinction of our method from single-mode implementations, due to the potential to output multiple optical traces at every measurement. As such, our method may enjoy other benefits commonly mentioned for multimode-based fiber sensors [29], onset from the ability to access multiple mode outputs with different optical properties. In the presented work, we demonstrated the simplest case, with the minimum possible number of modes in a few-mode circularly symmetric fiber. However, our method generalizes to fibers carrying a higher number of modes or coupled-core multicore fibers, so long as the conditions of having access to a pair of weakly coupled modes (or supermodes) with differing group velocities is fulfilled. The ability to access multiple optical trace outputs also opens new processing possibilities, which may range from simple averaging of incoherent sources of noise (as done in this work), to more advanced processing schemes aimed at preventing the onset of anomalous estimations from cross-correlation [51], and thus increasing the sensing dynamic while mitigating the consequent accumulation of 1/f noise [52].

We also note that our simple design can be readily adapted for different sensing paradigms, such as previously reported distributed transverse stress by the addition of simple processing steps, such as averaging of the optical traces acquired from each subsweep to produce an
incoherent measurement of the coupling strength envelope [6]. A demonstration of using our setup for incoherent measurements is presented in supplementary section 4.

Despite the remaining optimization efforts required for a field demonstration, we stress the potential of this design for future seismic sensing, in space-division multiplexed telecommunication links consisting of weakly coupled fiber links. Further investigation should provide answers on the compatibility and total interrogation range achievable with this technique in telecommunication-grade few-mode fibers (using in-line amplifiers), and what performances can be expected when using kilometer-length spatial resolutions. With the aim of ultralong range, kilometer-length spatial resolutions, and strain measurements in mind, a potential roadmap for future designs based on this technology may include the use of a mixed pulsed/swept approach, analogous to some works described in the Rayleigh-backscattering based sensing literature [17, 19]. This would entail restraining the total interrogated frequency range to a single wavelength channel, spanning multiple weakly coupled spatial channels. Our method can be adapted to such an implementation with only a few alterations to the hardware and processing scheme, by replacing the single-sweep approach into a multi-shot interrogation where the center frequency of each pulse is slowly modulated. This type of interrogation would benefit from the potential to co-propagate multiple pulses in the same fiber due to the transmission-based nature of the technique.

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**Data availability** All data in the main text or supplemental materials is available from the corresponding author upon reasonable request.

**Supplemental document** See Supplemental Document for supporting content.

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