

L-band dual-wavelength fiber ring laser with automated polarization stabilization and switching for remote sensing applications

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Abstract. This work reports the experimental demonstration of a dual-wavelength L-band fiber ring laser for remote sensing applications. The system incorporates a polarization-sensitive semiconductor optical amplifier as the gain medium and two fiber Bragg gratings placed 25 km away from the laser cavity using standard single-mode fiber that serve both as wavelength-selective elements and sensing heads. Wavelength switching between single- and dual-channel lasing configurations is enabled by a simplified two-paddle motorized polarization controller. The system achieves optical signal-to-noise ratios exceeding 55 dB and power differences between lasing lines as low as 0.01 dB. To ensure long-term stability, an automatic control algorithm dynamically adjusts the polarization state in real time, compensating for environmentally induced polarization drift. The proposed setup provides a compact and robust solution for polarization-based wavelength switching in fiber lasers, with applications in the field of remote optical sensing.

Keywords: Booster semiconductor optical amplifier, Fiber Bragg grating, Fiber-optic ring cavity laser, Polarization-switchable laser, Remote sensing.

1 Introduction

The development of single and multiwavelength fiber-based lasers has been an active area of research for decades, not only as they can serve as optical sources in the C-band of optical fiber communication systems, but also because of their applicability in fields such as sensing or spectroscopy, among others. While mostly developed for the C-band, there have been several proposals also for the L-band (1565–1625 nm), since their use in this wavelength range allows to increase the capacity of fiber links [1], the simplification and improvement of lidar systems [2], the extension of sensing systems to other contexts [3] and the application in spectroscopy systems [4]. An especially relevant example is the detection of carbon monoxide, carbon dioxide, methane, and other potentially harmful gases with absorption bands in the 1–2 μm spectral region, which has a clear impact in the protection of people and infrastructures in the oil and gas industries, water treatment plants, landfills, and commercial or domestic environments [5–7]. One of the most obvious advantages of using optical technologies in this context, the safety they offer by avoiding potentially flammable components, is reinforced if the sensor

head can be placed at a distance from the rest of the components, especially if the wavelengths can be remotely switched in order to enable the detection of different gases simultaneously. Switchable L-band multiwavelength lasers have been previously proposed for such applications, primarily based on fiber ring schemes [8]. Erbium doped fiber, which is the usual gain medium at lower wavelengths, presents a reduced emission cross-section beyond 1.6 μm . As a result, achieving sufficient gain at these longer wavelengths requires either longer fiber or higher doping concentrations. Additionally, the strong homogeneous broadening gain that Erbium doped fibers present leads to strong mode competition and results in poor laser stability. Addressing this issue requires the use of more complex setups or additional stabilization techniques [9–11]. Semiconductor optical amplifiers (SOAs) are consequently an interesting option as gain media in this wavelength region [12, 13]. In order to enable wavelength selection within the laser cavity, different optical filters are usually included into the ring structure, such as Fiber Bragg Gratings (FBGs) [14], Sagnac filters [8, 15] or Mach-Zehnder interferometers [16], among other techniques. Wavelength switching is typically accomplished by modifying the polarization state within the cavity, altering the ring cavity losses and, consequently, modifying the gain spectral distribution.

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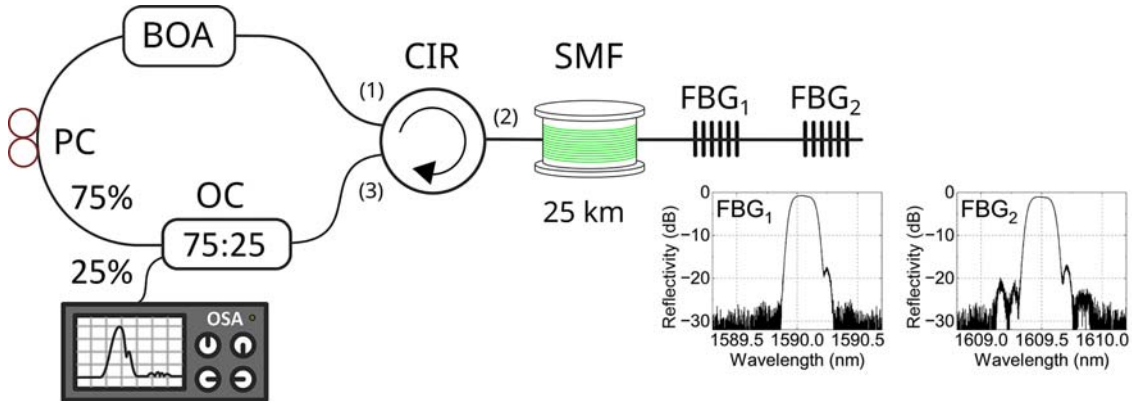


Fig. 1. Experimental setup of the proposed L-band multiwavelength remote sensor based on a motorized polarization-switchable fiber optic ring laser (BOA: Booster Optical Amplifier, PC: Polarization Controller, OC: Optical Coupler, CIR: Circulator, SMF: Single-Mode Fiber, FBG: Fiber Bragg Grating, OSA: Optical Spectrum Analyzer).

In [17] authors reported a system for remote sensing applications based on a switchable L-band fiber optic ring cavity laser incorporating a SOA and multiple FBGs. That study experimentally validated the capability of this architecture to detect temperature variations at remote locations. We demonstrated that by adjusting a motorized fiber polarization controller (PC) located 25 km away from the sensing head the system can be remotely switched between single-wavelength, dual-wavelength, and triple-wavelength lasing configurations. However, since the operation of the setup relies on the polarization properties of the components, the system exhibited limited stability, a common issue in polarization-sensitive architectures [10, 11, 18, 19]. In this work, a simplified version of the configuration described in [17] is presented, reducing the polarization control from three to just two paddles of a motorized PC to remotely achieve the desired wavelength selection. Furthermore, we implement an automatic control mechanism for the PC adjustment, resulting in significantly improved system stability over long periods of time. This approach effectively decouples the sensing information from power fluctuations: while the PC-tuning algorithm compensates for amplitude drifts in the power domain, the sensing data remain encoded in the wavelength shift of the spectral lines, ensuring that the measurement integrity is preserved.

2 Experimental setup

The experimental configuration of the laser system, depicted in Figure 1, is based on a fiber-optic laser operating at two distinct wavelengths and implemented using a ring cavity architecture. Notably, the system is implemented using non-polarization-maintaining elements, which represents a worst-case scenario as polarization fluctuations occur throughout the setup. While the use of polarization-maintaining components would likely result in a higher stability and enable a more deterministic output for a given PC configuration, the current setup allows for testing the robustness of the stabilization mechanism. A three-port optical circulator (CIR) is employed to control light propa-

gation within the ring cavity. Optical gain for lasing is provided by an L-band booster-type semiconductor optical amplifier (BOA, model S9FC1080P, from Thorlabs). The circulator directs the amplified signal from the BOA toward a reflective filtering module, enabling the filtered light to be re-coupled into the cavity and ensuring unidirectional propagation of the optical field.

Figure 2a presents the amplified spontaneous emission (ASE) spectra of the BOA at various driving current levels. At a driving current of 500 mA, the BOA exhibits a peak power of -29 dBm at 1583 nm with a 120 nm bandwidth. As observed, increasing the driving current result in both higher output power and a broader emission spectrum while the peak wavelength shifts toward shorter wavelengths. By design the BOA is inherently polarization-sensitive, amplifying only a specific linear polarization state. This property effectively makes the BOA act as a polarization-selective element within the laser cavity. To experimentally demonstrate this behavior, a PC followed by a polarization beam splitter (PBS) were employed to analyze the output polarization dependence as illustrated in Figure 2b. A Thorlabs MTC320 motorized controller was employed to alter polarization via stress-induced birefringence. By coiling single-mode fiber around independent spools to create fractional wave plates, the system, controlled by Thorlabs software, allows for precise polarization adjustment. This PC was used to align the amplification axis of the BOA with one of the PBS outputs. Under these conditions, at a bias current of 100 mA, the BOA delivers a peak output power of -44 dBm at a central wavelength of 1583 nm, consistent with the results shown in Figure 2a. However, nearly all the power is delivered to the aligned PBS output while the other output port, that corresponds to the orthogonal linear polarization state, is close to the noise level, as depicted in Figure 2c.

As shown in Figure 1, a PC included at the BOA input port allows precise adjustment of the cavity polarization-dependent loss spectrum and, thus, switching between different wavelength emission configurations. Most lasers that incorporate a PC to ensure emission at specific wavelengths rely on the fact that only a particular state of polarization

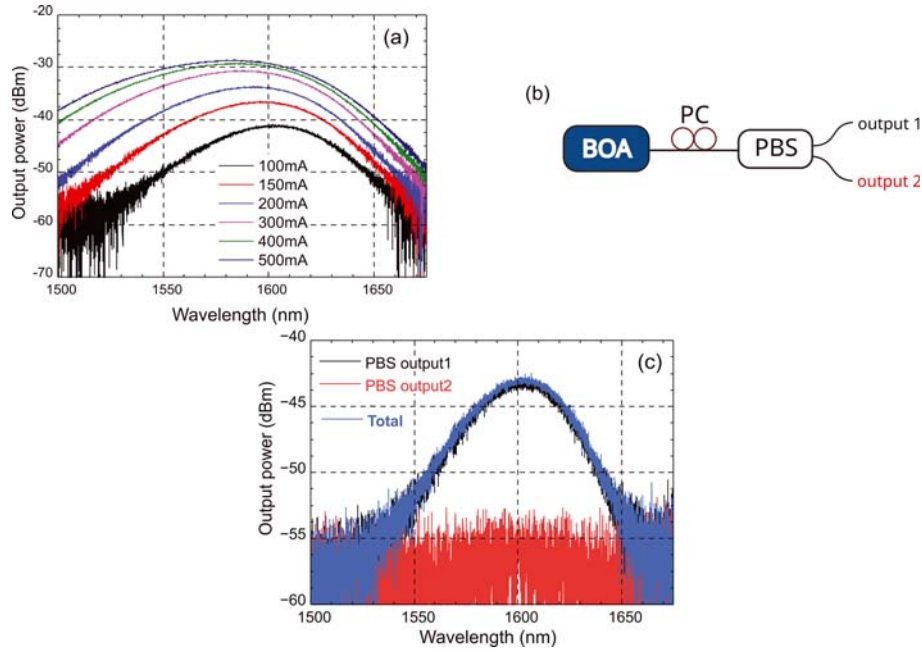


Fig. 2. (a) ASE spectra at BOA's output for different driving currents; (b) Experimental setup employed for evaluating BOA's polarization dependence; (c) Output power spectra at the PBS output ports.

(SOP) can resonate within the cavity [20–22]. In conventional three-paddle PCs, formed by a cascade of three retarder plates in the form QWP–HWP–QWP (QWP: quarter-wave plate, HWP: half-wave plate), precise adjustment of the orientations of the three paddles allows an arbitrary input polarization to be transformed into a well-defined output SOP [23], thereby enabling resonance at the wavelength associated with that polarization state. In contrast, in the present work, a reduced two-paddle PC, consisting of a QWP followed by an HWP, is employed. Although this configuration cannot generate an arbitrary SOP independently of the input, Jones-matrix analysis shows that it is sufficient to convert a general elliptical polarization into a linearly polarized state with a controllable orientation by proper adjustment of the plates' angles [24]. When combined with the strong polarization-dependent gain of the BOA, which is shown in Figure 2c, this linear polarization rotation translates into distinct cavity gains for different SOPs, enabling polarization-selective amplification and wavelength switching without the need for a full three-paddle PC. Hence, with only two paddles to be adjusted instead of the usual three, the tuning process for selecting the desired lasing configuration becomes simpler and faster. The ring is closed with a 75:25 coupler that extracts part of the generated light for its measurement with an optical spectrum analyzer with a resolution of 0.03 nm, (OSA, model MS9740B-009, from Anritsu).

The filter used to define the emitted lines wavelengths is constructed by concatenation of two FBGs. Their central wavelengths, 1590 nm (FBG₁) and 1610 nm (FBG₂), are positioned within the BOA's L-band ASE spectrum. As illustrated in Figure 1, both FBGs exhibit a 0.22 nm bandwidth with reflectivities of −0.75 dB and −1.05 dB, respectively. Despite a minor mismatch in reflectivities, the

variation is insufficient to inhibit dual-wavelength operation. Besides their filtering function, these FBGs are separated from the rest of the setup by a 25 km spool of single mode fiber (SMF), serving also as the remotely controlled sensing mechanism, as demonstrated in [17], and enabling long distance sensing applications. All experimental measurements were conducted at room temperature, and no vibration isolation or temperature compensation techniques were employed.

3 Results

The switchable operation of the system is validated by driving the BOA at bias currents of 250, 300, and 350 mA, with all measurements performed at room temperature. The laser emission configuration is controlled by adjusting the rotation of both PC paddles. To explore the full range of possible operating modes under different biasing conditions, all configurations – namely no-lasing, single-wavelength, and dual-wavelength states – are systematically tuned using a search algorithm. This algorithm evaluates all possible paddle configurations of the motorized PC and optimizes different parameters depending on the target configuration. For single-wavelength and no-lasing states, the paddle positions are optimized to maximize suppression of undesired emission lines. For dual-wavelength operation, the optimization minimizes the optical power difference between the two lasing peaks, ensuring balanced output across both channels.

An example of the tunability of the system can be seen in Figure 3. In this example, the QWP is held fixed while the HWP is rotated to different positions with a 5-degree resolution. As shown, different combinations of optical

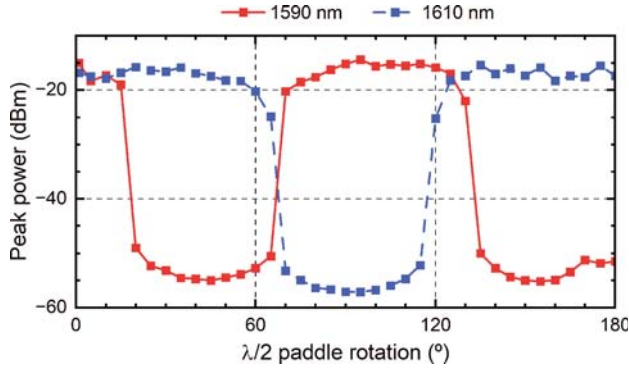


Fig. 3. Optical peak power for each emission wavelength as a function of the HWP adjustment, with the QWP held fixed.

power for the emission wavelengths can be achieved depending on the paddle positions. Therefore, by simultaneously adjusting both paddles, an optimization process can be performed to obtain the desired output combinations.

The results of the tuning process for all lasing configurations at a bias current of 300 mA are shown in Figure 4. Figure 4a corresponds to the no-lasing configuration, where both emission wavelengths exhibit a power level below -45 dBm. In contrast, the single-wavelength emission configurations presented in Figures 4b and 4c show that both emission lines exceed a peak optical power of -15 dBm, resulting in an optical signal-to-noise ratio (OSNR) greater than 55 dB in both cases, as well as a main lobe-to-sidelobe suppression ratio (MSSR) exceeding 40 dB. Finally, Figure 4d illustrates the dual-wavelength configuration, where the peak output power of each emission wavelength is -11.84 dBm. The power difference measured in this configuration is less than 0.01 dB, and the OSNR for both wavelengths is higher than 60 dB. These parameters align with established standards for high-performance laser-sensing in the C [25], O [26], and L-bands [3].

Table 1 provides a comprehensive summary of the results obtained for all configurations across the three bias current levels. The data include the power OSNR of each emission line, along with the power difference between both lines for each configuration. The results are consistent across all cases, with only minor variations attributed to increased available power at higher bias currents. In all non-lasing cases, line suppression exceeds 42 dB, while in all single-line emission configurations, the MSSR is at least of 37 dB and the OSNR is greater than 55 dB. For the dual-wavelength emission configuration, the OSNR surpasses 58 dB in all cases, with the maximum power difference between emission lines remaining below 0.5 dB and reaching as low as 0.01 dB in one instance, demonstrating an exceptional level of output equalization. It is worth noting that these results could be further improved with enhanced polarization control, which was limited in this study by the motorized controller's minimum rotation angle of 0.2° . Nonetheless, the results validate the proposed system and demonstrate its ability to maintain high performance under varying operational conditions.

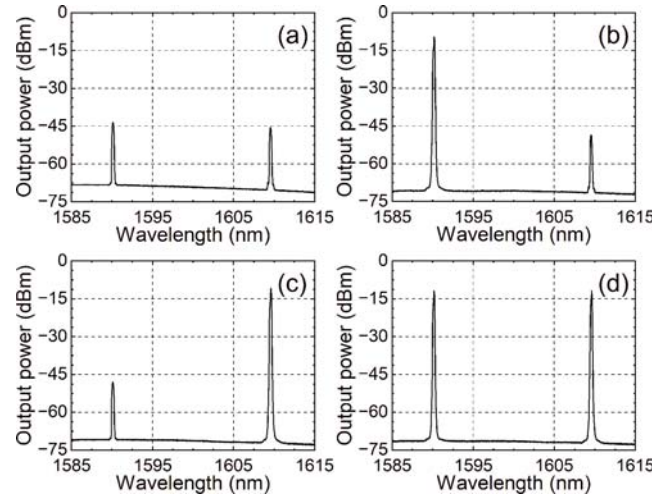


Fig. 4. Output spectra measured in the optical domain for the: (a) no-lasing, (b) single-wavelength at 1590 nm (c) single-wavelength at 1610 nm and (d) dual wavelength lasing configurations, for a biasing current of 300 mA at the BOA.

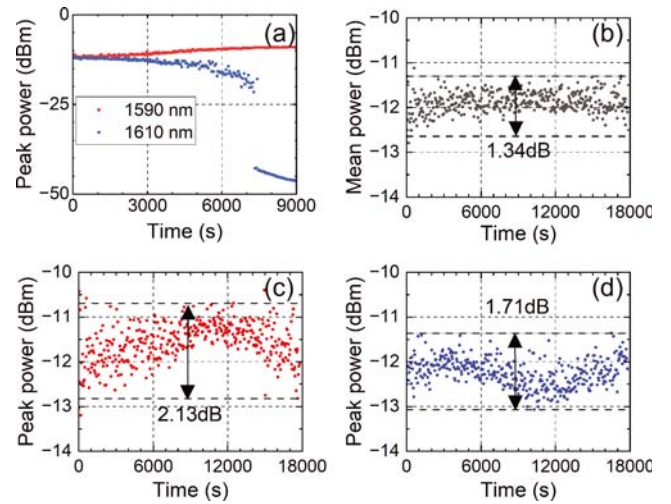


Fig. 5. (a) Output peak powers for a dual-wavelength configuration in free-running mode; (b) mean peak power; (c) 1590 nm and (d) 1610 nm peak for the dual-wavelength configuration with the stabilization loop activated, indicating the CL at 95% (dashed lines).

The dual-wavelength configuration with a 300 mA bias current was chosen to evaluate the stability of the system. First, output spectra were captured every 45 s for a total of 2.5 h, without any adjustments of the PC during all the experiment duration. The registered evolution of the two wavelengths peak powers is plotted in Figure 5a, showing that the system is not able to preserve the dual-wavelength emission, since the 1610 nm line power progressively decreases and eventually falls drastically after approximately 2 h, becoming then the laser a single line device. This behavior prevents the use of this free-operating

Table 1. Switching results for different configurations and biasing currents.

		Peak power (dBm)		OSNR (dB)		Peak power diff. (dB)
		λ_1	λ_2	λ_1	λ_2	$\lambda_1 - \lambda_2$
250 mA	No-lasing	-52.2	-52.4	18.8	18.6	0.2
	λ_1 lasing	-10.1	-51.9	61.8	20.1	41.8
	λ_2 lasing	-48.8	-11.9	23.2	60.0	36.9
	$\lambda_1 + \lambda_2$ lasing	-12.7	-13.1	59.4	58.8	0.5
300 mA	No-lasing	-43.5	-45.6	25.5	23.4	2.0
	λ_1 lasing	-9.7	-48.3	61.0	22.0	38.9
	λ_2 lasing	-48.1	-10.8	22.7	60.0	37.3
	$\lambda_1 + \lambda_2$ lasing	-11.8	-11.8	59.5	59.5	0.0
350 mA	No-lasing	-49.4	-50.0	21.1	20.5	0.6
	λ_1 lasing	-8.3	-50.7	62.2	19.8	42.4
	λ_2 lasing	-54.0	-14.4	16.9	56.6	39.6
	$\lambda_1 + \lambda_2$ lasing	-10.7	-10.8	60.0	60.0	0.1

setup in optical sensing applications requiring stable long-term dual wavelength operation.

Since the cause of the undesired variations of the generated spectrum are the unavoidable random fluctuations of the polarization state of the light propagating within the ring, an automatic control loop was included to respond and recover from these oscillations. The operational procedure of the control loop begins with an initialization phase to identify a reference angular configuration that achieves the desired spectral configuration. Once this configuration is achieved, the system continuously monitors the optical power spectrum and triggers a local search algorithm if the difference between the peak powers of the desired spectrum and the measured spectrum exceeds a 1 dB threshold. This search prioritizes the HWP due to its critical impact on equalization, testing positive and negative angular variations of increasing magnitude until an error below 0.5 dB is achieved again. Should no valid equalization be found by rotating only the HWP, the algorithm selects the best-performing angle and subsequently adjusts the QWP rotation to identify the optimal combination within the search interval by following a similar procedure. While this mechanism significantly improves the management of slow drifts, the search process itself introduces transient fluctuations, such as momentary drops in emission lines, indicating that the current implementation is not yet fully optimized for all operating conditions. However, as undesired polarization fluctuations typically occur at slower rates than the time required for the control loop to reoptimize the PC positions, this scheme correctly anticipates and prevents significant deviations in the produced spectrum, resulting in an important improvement on the stability over long periods of continuous operation of the laser. When the control loop is enabled, the output spectrum remains stable, as demonstrated in Figures 5b–5d, over an extended 5 h recording period. In Figure 5b the mean value of the peak powers for both wavelengths is presented, where the maximum fluctuation of the signal is 1.34 dB for a 95% confidence level (CL). Additionally, Figures 5c–5d show the peak powers of each wavelength, which present a maximum fluctuation of 2.13 and 1.71 dB respectively for a 95% CL.

These fluctuations could potentially be further reduced, since the algorithm currently adjusts the PC paddles only when the power difference between the two lines exceeds a predefined threshold, without accounting for the individual variation trends. Additionally, as previously noted, the resolution of the control is constrained by the minimum rotation step of the paddles in our device, which is 0.2°.

4 Conclusion

A multiwavelength switchable fiber ring laser operating in the L-band for sensing applications has been experimentally demonstrated. The system is based on a polarization-sensitive SOA as the gain medium and two FBGs that define the emitted wavelengths and that can simultaneously function as remote sensing elements. The FBGs were deployed 25 km from the system header via standard single-mode fiber, thereby enabling long-range remote sensing applications. The laser can be electronically switched at the header between all emission configurations – no lasing, single-wavelength, or dual-wavelength operation – with OSNR consistently exceeding 55 dB, MSSR of at least 37 dB, and power differences between lasing lines in the dual-wavelength configuration below 0.5 dB. Wavelength switching is enabled by a simplified motorized polarization controller composed of only two paddles (a QWP followed by a HWP), without the need for additional polarization-dependent elements. This configuration supports automatic control, enabling stable long-term operation without the need for environmental isolation or polarization-maintaining fiber thanks to a closed loop algorithm that self-stabilizes the output by fine-tuning the paddles rotations.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

The datasets generated and/or analyzed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

Author contribution statement

Conceptualization, S.T., M.J.E. and R.A.P-H.; Methodology, S.T., M.J.E. and R.A.P-H.; Software, A.S., A.S-G., S.T., M.J.E. and R.A.P-H.; Validation, A.S., I.J., U.S-M, A.S-G.; Formal Analysis, S. T, M.J.E. and R.A.P-H.; Investigation, S.T, M.J.E., A. S-G. and R.A.P-h.; Resources, S.T., M.J.E. and R.A.P-H.; Data Curation, A.S., I.J., U.S-M, A.S-G.; Writing – Original Draft Preparation, S.T, M.J.E. and R.A.P-H.; Writing – Review & Editing, S.T., A.S., I.J., U.S-M, A.S-G., M.J.E. and R.A.P-H.; Visualization, A.S., I.J., U.S-M, A.S-G.; Supervision, S.T., M.J.E. and R.A.P-H.; Project Administration, S.T., M.J.E. and R.A.P-H.; Funding Acquisition, S.T., M.J.E. and R.A.P-H.

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