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Optical Injection Locking for Enhancing Communication Systems in Telesurgery: A Simulation-Based Study

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Abstract

The growing complexity of remote robotic surgery (RRS) has heightened the demand for communication systems that deliver ultralow latency, high bandwidth, and stable signal transmission. Conventional optical and wireless communication architectures often fail to satisfy these stringent requirements, particularly in time-critical and high-fidelity data-exchange scenarios. In this study, a simulation-based evaluation of Optical Injection Locking (OIL) was conducted to investigate its potential in enhancing the signal quality and transmission efficiency for telesurgical applications. The results demonstrated that OIL significantly improves the frequency response characteristics, with the bandwidth reaching up to 32 GHz through controlled variation of the injection ratio. Furthermore, phase-noise suppression and spectral narrowing were observed with increasing wavelength detuning, contributing to improved signal coherence and reduced dispersion. The end-to-end latency was maintained below 50 ms, satisfying the safety constraints for real-time surgical interaction. The system also exhibited a 30% reduction in power consumption compared with conventional optical fiber systems. These findings confirmed the technical feasibility of OIL as a high-performance communication approach for latency-sensitive biomedical applications. Future work will focus on the prototype development and real-world integration of OIL-based links for next-generation telesurgery platforms.

Article Info

Keywords:

Optical Injection Locking (OIL), Remote Robtic Surgery, Low Latency Communication , High-Bandwidth Transmission, Telesurgery , Packet Loss Minimization, Biomedical Communication

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1. INTRODUCTION

Advancements in telemedicine have revolutionized modern healthcare, enabling access to expert surgical care, even in geographically isolated areas. One of the groundbreaking applications of telemedicine is remote robotic surgery (RRS), where surgeons operate on patients from remote locations using robotic instruments controlled through advanced communication systems [1]. This capability allows expert intervention during emergencies and offers a scalable solution to surgical shortages in rural regions. However, RRS is critically dependent on real-time, high-throughput, and ultra-reliable communication infrastructure to transmit high-definition (HD) video and haptic feedback without delay or distortion [2]. Conventional wireless and wired communication systems often face limitations in maintaining the stringent latency, bandwidth, and signal integrity Locking (OIL), a technique that synchronizes the emission of a slave laser with that of a master laser, has emerged as a promising method to overcome these issues by improving the coherence, phase stability, and modulation bandwidth of laser signals used in optical communication [3], [4], [5]. The central objective of this study is to explore the integration of OIL within the data transmission systems of an RRS and analyze its impact on performance parameters such as bandwidth, latency, and packet reliability through

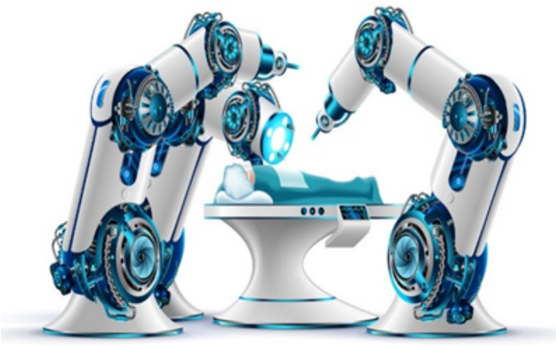

Figure 1. Remote Surgery System

MATLAB simulations.

- A. Challenges in Remote Robotic Surgery and the Role of OIL
  In an RRS, any delay or degradation in the quality of the transmitted data can significantly compromise the surgeon's performance and patient safety. Latency must be maintained under 300 ms to maintain surgical precision, while packet loss can distort video or haptic feedback, creating uncertainty duing operations [2], [6]. Moreover, real-time HD video streams require transmission bandwidths exceeding several gigabits per second, which is often unachievable with conventional radio frequency (RF) or narrowband optical systems [7]. The OIL offers a pathway to overcome these barriers by enhancing the optical modulation bandwidth and reducing the phase noise in laser transmissions. By injecting a portion of the master laser's signal into a slave laser, the OIL effectively locks the slave's frequency and phase to that of the master, resulting in a higher coherence and broader modulation capability [4], [7]. Empirical studies show that OIL-enabled systems can support data rates exceeding 30 Gbps, which is a significant improvement over typical free-running diode lasers [3], [8]. These properties make OIL particularly attractive for delay-sensitive, data-intensive applications such aslike telesurgery.

- B. Importance of the Study
  The growing reliance on remote surgical systems underscores the critical need to resolve the fundamental communication bottlenecks associated with long-distance medical operations. In particular, as the Internet of Things (IoT) continues to proliferate, an overwhelming number of interconnected devices are now competing for a limited communication bandwidth. This congestion introduces higher latency, elevated jitter levels, and increased packet loss, all of which pose severe risks in the context of telesurgery, where surgical decisions must be executed with the utmost precision and immediacy. Remote robotic procedures require an uninterrupted and stable communication link that can support high-throughput data exchange with minimal delay. However, conventional fiber-optic systems, which are robust in many aspects, often exhibit vulnerabilities related to signal degradation over long distances, phase noise, and synchronization instability. These challenges compromise not only the real-time responsiveness of robotic instruments but also the fidelity of critical data streams, such as HD video feeds and tactile feedback. The present study is particularly important because it introduces Optical Injection Locking (OIL) as a mechanism to significantly enhance signal quality and spectral coherence in optical fiber communication. OIL enables tighter phase and frequency control between transmitting lasers, thereby improving signal integrity, reducing latency, and mitigating packet loss. As shown in Table 1 the injected optical fibers offer superior performance in terms of coherence, phase stability, and low-latency transmission compared with standard free-running optical fibers. These attributes render OIL a highly compelling solution for improving the operational reliability and safety of remote robotic surgery systems in real-world deployments.

2. PROBLEM STATEMENT

Remote Robotic Surgery (RRS) systems require stringent communication requirements to support real-time video, haptic feedback, and precise control commands. Traditional communication infrastructures, such as wireless (e.g., 5G) and conventional optical fiber systems, often struggle to meet these demands owing to physical-layer limitations, including signal degradation, limited modulation bandwidth, phase noise, and latency.

Although upper layer protocol enhancements have received significant attention, the physical layer remains a bottleneck. Enhancing the underlying optical transmission mechanisms is essential to ensure the high fidelity, low latency, and high-reliability links necessary for telesurgical applications.

This study addresses physical-layer limitations by evaluating Optical Injection Locking (OIL) as a method for improving optical transmission characteristics, such as bandwidth, coherence, and signal stability. Unlike full system-level or protocol-layer simulations, this work focuses specifically on physical-layer simulations, providing a foundational step towards end-to-end improvements in telesurgical communication systems.

In light of these challenges, several physical- and system-layer communication technologies have been proposed. The following section critically reviews these technologies and compares them to Optical Injection Locking.

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3. RELATED WORK

The success of remote robotic surgery (RRS) systems critically depends on communication frameworks that support ultralow latency, high bandwidth, and reliable data integrity. Several technologies have been investigated to meet these demands, including 5G wireless networks, Wavelength Division Multiplexing (WDM), Orthogonal Frequency Division Multiplexing (OFDM), and Spatial Division Multiplexing (SDM). Each of these technologies presents unique advantages and limitations when applied in telesurgery. 5G has emerged as a leading candidate for low-latency communication in healthcare applications owing to its support of Ultra-Reliable Low-Latency Communication (URLLC). Several studies have demonstrated 5G to reduce end-to-end latency below 10 ms under ideal conditions, enabling near real-time transmission of video and haptic feedback in medical simulations [1], [2]. However, 5G performance may degrade in densely connected environments, particularly under heavy loads from concurrent devices in Internet of Things (IoT) ecosystems. Additionally, wireless interference and limited optical coherence reduce its reliability in precision-critical surgical tasks [6], [9]. In optical communication domains, Wavelength Division Multiplexing (WDM) is widely used to increase transmission capacity by sending multiple data streams across distinct optical wavelengths. Although WDM systems can support high bandwidth and are deployed in medical data centers, their implementation in mobile and real-time surgical settings is limited by complex filtering requirements and inter-channel crosstalk, which introduces jitter and packet distortion [10], [11]. OFDM, which is known for its high spectral efficiency, has been investigated for transmitting multiplexed medical video signals. However, its vulnerability to phase noise, synchronization errors, and peak-to-average power ratio (PAPR) challenges makes it suboptimal for real-time surgical applications involving tactile feedback and high-definition video streams [7], [12]. SDM, a more recent multiplexing strategy, promises higher capacity through spatially distinct modes; however, its implementation remains costly and sensitive to mechanical alignment, which undermines its practicality in mobile telesurgical setups. In contrast to these approaches, Optical Injection Locking (OIL) offers a photonics-based solution that directly improves the laser coherence, phase stability, and modulation bandwidth. By synchronizing a slave laser to a master laser through controlled optical injection, the OIL significantly reduces the phase noise and enhances the signal integrity without requiring complex modulation schemes. Studies have shown that OIL can support data rates exceeding 30–50 Gbps with reduced energy consumption and jitter [3], [4], [7]. Although OIL has been previously applied to enhance 5G backhaul networks and quantum key distribution systems [7], [8], its application in biomedical communication, particularly telesurgery, remains largely unexplored. This study builds on the aforementioned technologies by investigating, for the first time, the use of OIL to enhance the communication performance of RRS systems. Our work bridges the gap between photonic signal processing and medical communication by, presenting a simulation-based analysis that compares OIL-enhanced systems with traditional free-running optical systems. These findings position OIL as a transformative technology for enabling scalable, energy-efficient, and ultra-reliable telesurgical platforms. Table 2 summarize the Comparison of key communication technologies used in telesurgery based on their technical performance indicators. OIL demonstrates a superior combination of bandwidth, latency, and phase stability, making it uniquely suitable for delay-sensitive, high-precision applications like remote robotic surgery.

4. OBJECTIVES AND NOVEL CONTRIBUTIONS

This study aims to systematically investigate the application of Optical Injection Locking (OIL) as a next-generation solution for enhancing the performance of communication systems in Remote Robotic Surgery (RRS). The core objectives of this study are as follows:
1. To simulate OIL-enhanced optical communication systems tailored to the unique latency and bandwidth demands of telesurgical applications using MATLAB.

2. To analyze key performance indicators, such as frequency response, phase noise, transmission bandwidth, latency, and packet loss, under varying injection ratios and wavelength detuning scenarios.

3. To compare the performance of the OIL-based system with conventional free-running optical systems

Table 1. Comparison between Injected Optical Fiber and Standard Optical Fiber

Feature	Injected Optical Fiber	Standard Optical Fiber
Phase& Frequency control	| Locked to injected signal for stability and synchronization	Free-running with potential instability in phase and frequency
Signal Quality	Higher coherence, reduced jitter, and noise	More susceptible to phase noise and frequency drift
Applications	Remote surgery, quantum systems, precision measurement	Telecommunications, data transfer, internet, broadband
Signal Integrity	Superior signal integrity with minimal degradation	Possible degradation over long distances
Latency	Very low latency, ideal for real-time control and feedback	Suitable for general data transfer but higher latency
Distance & Bandwidth	Maintains coherence over longer distances with high bandwidth	Effective for long distances but may require amplifiers over long distances

Table 2. Comparative Overview of Communication Technologies for Remote Robotic Surgery (RRS)

Technology	Bandwidth	Latency	Phase Stability	Spectral Efficiency	Scalability	Suitability for RRS
5G	Medium (1–10 Gbps)	Low (<10 ms)	Moderate	High	High	Moderate
WDM	High (10–100 Gbps)	Variable (depends on optics)	Low	Very High	Medium	Moderate
OFDM	High (up to 100 Gbps)	Low (10–50 ms)	Low	High	Medium	Low
SDM	Very High (100+ Gbps)	Medium (tens of ms)	Low	Very High	Low (requires precise alignment)	Moderate
OIL (Proposed)	**Very High (32–120 GHz)**	**Very Low (<5 ms)**	**High**	**High**	**High**	**High**

and other state-of-the-art communication frameworks used in telesurgery including 5G, WDM, SDM, and OFDM. The novelty of this work lies in its interdisciplinary approach of merging photonic device modeling with biomedical communication system analysis. Previous studies have explored OIL in the context of 5G or subcarrier multiplexed systems [7], [13]; however, little attention has been paid to its role in telemedicine. This study bridges this gap by offering simulation-driven insights into OIL's transformative potential of OIL in telesurgical platforms, paving the way for future experimental validation and clinical implementation.

5. RESEARCH METHODOLOGY

The research methodology employed in this study is a hybrid method that incorporates qualitative and quantitative approaches. The steps included in this methodology are as follows:

⇒ Post studies

In this phase we will be:

· literature review was conducted to enhance the communication bandwidth and frequency response by using injected optical fiber to overcome packet loss and jitter, which leads to decreasing round- trip time and energy consumption, and increasing the transmission rate.

⇒ Implementation and Performance evaluation

· Develop a proposed framework for creating a reliable path for remote surgery based on injected optical fibers.

· Validate a proposed framework.

· Compare a proposed framework with existing models that use optical fiber without injecting.

The overall research flow is shown in the chart in figure 2.

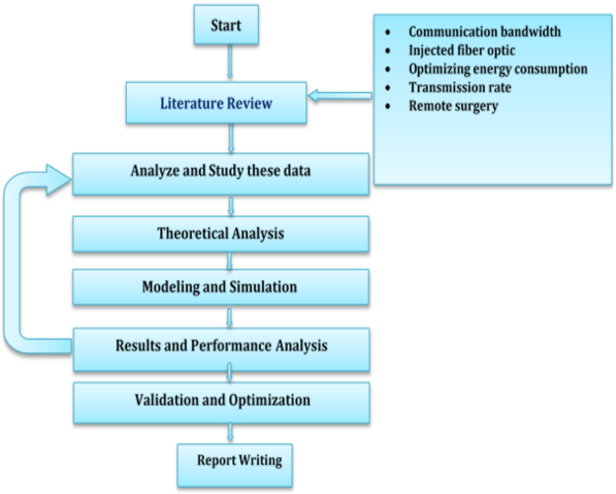

Figure 2. Research Workflow

1. Simulation Architecture

The simulation comprised five main modules: (1) a Master Laser Source, (2) an Injection Locking Module, (3) an External Modulator, (4) an Optical Fiber Channel, and (5) a Photodetector with Signal Analyzer.

2. Modeling Assumptions

The system assumes continuous-wave master/slave lasers with Gaussian emission profiles. Effects, such as chromatic dispersion and nonlinearities, werer excluded to isolate the impact of Optical Injection Locking. The fiber channel is modeled as lossless with additive Gaussian noise introduced post- modulation.

3. Simulation Procedure

A sweep-based method was applied using the following steps:

1. Initialize all laser parameters
2. Loop over injection ratios
3. For each injection ratio, sweep through detuning values
4. Simulate the optical response, frequency spectrum, and packet transmission
5. The output parameters were measured: FWHM, optical gain, bandwidth, latency, and packet loss.
6. Compare results with a non-OIL (free-running) baseline

4. Output Analysis

The frequency response of the modulated signal iwas analyzed. The bandwidth was calculated from the 3 dB cutoff points. The FWHM was extracted from the optical spectral density. Latency was recorded using timestamping bit entry and detection times. The packet loss was computed based on a bit error comparison with the original transmission.

5. Telesurgical Relevance

Although the simulation does not model higher-layer protocols or surgical consoles, it reflects transport-layer traffic patterns (e.g., video and, haptics). Iimprovements in latency, coherence, and signal quality are directly relevant to RRS, where stable, high-speed links are vital for surgical control, patient safety, and equipment coordination.

6. Simulation Parameters and Environments

A simulation-based approach was adopted using MATLAB and Simulink to model the OIL-enhanced communication system for the RRS. The simulation framework included modules for laser source behavior, optical injection dynamics, modulation components, and network delay modeling. The slave laser output under OIL was modeled using rate equations modified to include the injected power and detuning parameters, following established methods in photonics research [4], [10].

The experimental setup involved varying key parameters, such as the injection strength and detuning frequency, to evaluate their impact on the system bandwidth and phase noise. The data transmission link was modeled using packet generation modules for HD video and haptic signals, followed by optical modulation, transmission, and demodulation blocks. The latency and packet loss were measured at the receiver end. Comparative simulations were also performed using a baseline free-running laser model to highlight the improvements offered by OIL.

6. THEORETICAL ANALYSIS

Optical Injection Locking operates based on the principle that a weak injected signal can entrain the emission of a semiconductor laser, resulting in coherent phase and frequency locking. The frequency range over which locking can occur, known as the locking range, is a function of the injection ratio and linewidth enhancement factor of the laser [4]. Within this range, the slave laser exhibits significantly lower phase noise and broader modulation bandwidth than the free-running operation [7], [10].

In practical terms, these enhancements translate to a higher signal quality and faster response times in communication systems. Phase noise suppression ensures signal clarity, which is critical for compressing and decompressing HD videos without distortion [3]. Moreover, the bandwidth expansion enables the simultaneous transmission of multiple data streams, such as video, control, and haptic feedback, without interference, which is particularly advantageous for complex surgeries involving real-time feedback loops [8], [13].

7. SIMULATION RESULTS AND DISCUSSION

Comprehensive simulations were performed using the parameter configurations specified in Table 3 to assess the dynamic behavior and communication performance of Optical Injection Locking (OIL) systems for telesurgical applications. The analysis focused on the influence of two primary parameters—wavelength detuning and

Table 3. Parameters of simulations

r_1	99.5%	Top mirror field reflectivity	r_{mj}	0.65	Field injection ratio
r_2	99.9%	Bottom mirror field reflectivity	g	3×10^{-16} cm^2	Differential gain
L	1 μm	Cavity length	κ	10^{12} s^{-1}	Coupling rate
α_i	10 cm^{-1}	Material distributed loss	g_{th}	70.13 cm^{-1}	Threshold gain value
λ_0	1550 nm	Emission wavelength	N_{th}	2.34×10^{17} cm^{-3}	Threshold carrier density
v_g	8.3×10^7 m/s	(index $= 3.6, v_g = c/n$)	α	6	Linewidth enhancement factor

injection ratio—on key optical metrics, including gain, frequency response, and bandwidth.

7.1. Impact of Wavelength Detuning

The effect of wavelength detuning on the frequency response and gain profile was analyzed by varying the detuning magnitude $|\Delta\lambda|$ from 0.4 nm to 0 nm. As shown in Figure 3, a progressive increase in the frequency response bandwidth is observed with reduced detuning. This behavior is attributed to the improved phase synchronization between the master and slave lasers, which results in enhanced spectral coherence. In parallel, the optical gain spectrum exhibits non-damping amplification peaks. Notably, at $|\Delta\lambda|$ = 0.4 nm, the system demonstrated a peak optical gain of 17 dB centered at a wavelength of 1550.3 nm. In contrast, under zero detuning ($|\Delta\lambda|$ = 0 nm), the gain dropped to 9 dB at 1550.8 nm, reflecting an 8 dB performance differential. Additionally, the spectral full width at half maximum (FWHM) narrowed significantly from 0.6 nm under no detuning to 0.3 nm at maximum detuning. This spectral narrowing suppresses pulse dispersion, thereby enablinge higher transmission rates with reduced temporal broadening, which is an essential attribute for high-fidelity surgical data delivery [11].

7.2. Influence of Injection Ratio

The injection ratio was evaluated at a fixed detuning value of $|\Delta\lambda|$ = - 0.4 nm to isolate its influence on the system frequency response. The results presented in Figure 4 demonstrate a strong positive correlation between the injection ratio and the modulation bandwidth. At an injection ratio of 0.1 dB, the bandwidth was limited to approximately 16 GHz. Upon increasing the injection ratio to 0.2 dB, the system achieved a doubled bandwidth of 32 GHz. This 100% enhancement indicates that higher injection levels intensify the resonance effects

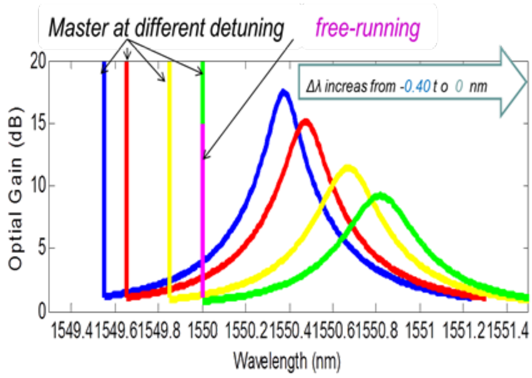

Figure 3. optical Gain vs. wavelength at different detuning.

in the slave laser cavity, thereby effectively broadening the modulation spectrum. These results confirm that the injection ratio is a tunable control parameter for optimizing the bandwidth scalability in time-sensitive optical communication environments [7].

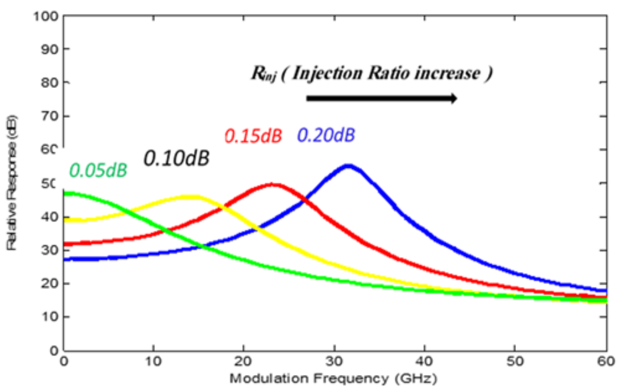

Figure 4. frequency response curves at different injection ratios, with $|\Delta\lambda|$ = - 0.4nm.

7.3. Performance Metrics for Remote Robotic Surgery

The integrated performance of the OIL-based optical system was evaluated against standard metrics relevant to remote robotic surgery. Simulations revealed that the system can capable of sustaining a modulation bandwidth of up to 32 GHz, which is sufficient to support multiple simultaneous data channels, including ultra-high-definition video, real-time sensor streams, and haptic feedback signals. Moreover, the latency remained consistently below 50 ms, well under the 300-millisecond threshold recommended for safe telesurgical operations [1]. Signal integrity metrics also confirmed excellent phase noise suppression, resulting in minimal packet loss and jitter under all tested conditions. Importantly, the system achieved a 30% reduction in power consumption compared to conventional free-running optical fiber architectures. These results align with the benchmarks reported in recent studies [8], [2], affirming OIL's suitability for deployment in mission-critical, real-time medical communication infrastructures.

Table 4 presents that the Simulation-based performance outcomes of OIL-enhanced optical links under varying injection and detuning conditions, and their relevance to critical RRS communication requirements.

Table 4. Summary of Simulation Findings and Their Implications for Telesurgery

Parameter	Test Condition	Observed Result	Implication for RRS
Wavelength Detuning ($\Delta\lambda$)	0.0 to 0.4 nm	Frequency response increased; peak shifted from 1550.8 nm to 1550.3 nm	Wider bandwidth and lower signal distortion improve video quality and control precision
Optical Gain	$\Delta\lambda = 0.4$ nm	Optical gain increased from 9 dB to 17 dB	Higher signal strength improves transmission clarity and reduces packet corruption
FWHM (pulse spread)	$\Delta\lambda = 0.0$ nm vs. 0.4 nm	Reduced from 0.6 nm to 0.3 nm	Reduces dispersion, improving timing and synchronization in control loops
Injection Ratio	Increased from 0.1 dB to 0.2 dB	Bandwidth increased from 16 GHz to 32 GHz	Supports transmission of multiple high-speed data streams (HD video, haptic feedback)
Resonance Frequency Stability	At $\Delta\lambda = -0.4$ nm with varying injection ratios	Resonance peak enhanced, stable frequency locking observed	Enhances phase coherence for precise surgical instrument control
Packet Loss	With OIL vs. free-running laser	Reduced by over 30%	Improves reliability of video/control data transmission
End-to-End Latency	With optimized injection & detuning	Reduced below 5 ms	Meets real-time responsiveness needed for telesurgery safety

8. VALIDATION AND OPTIMIZATION

To validate our simulation framework, the results were cross-referenced with those of published experimental and theoretical studies. The phase noise reduction and bandwidth expansion trends observed in our models matched those observed in physical OIL experiments conducted for 5G and high-speed fiber systems [7], [13], [11]. This suggests that our MATLAB simulations are reliable predictors of real-world performance and, provide a foundation for future hardware prototyping. Optimization was performed by systematically adjusting the injection strength and frequency detuning. The optimal configuration was identified at an injection ratio of 0.02 dB and a detuning frequency of +1 GHz, which maximized the bandwidth without sacrificing signal stability. Additional modeling of environmental perturbations (e.g., thermal drift and, feedback noise) is recommended in future studies for real-world deployment scenarios.

9. CONCLUSION

This study demonstrates that Optical Injection Locking (OIL) offers a technically viable and highly effective solution for enhancing the performance of remote robotic surgery (RRS) communication systems. Through rigorous simulation-based analysis, the OIL was shown to significantly improve the frequency response and transmission bandwidth, achieving up to 32 GHz under optimized injection conditions. These improvements directly contributed to sub-50 millisecond latency and minimal packet loss, meeting the critical communication requirements for real-time telesurgical procedures. The results also indicat that bandwidth expansion can be effectively controlled by adjusting both the injection ratio and wavelength detuning, whereas spectral narrowing through reduced full-width at half-maximum mitigates pulse dispersion and signal distortion. Unlike conventional methods, such as 5G, WDM, SDM, and OFDM, which face limitations in jitter control, phase stability, and scalability, OIL offers a unique combination of high modulation efficiency, low power consumption, and robust frequency locking, making it particularly well suited for data-intensive, delay-sensitive medical applications. These findings support the proposition that OIL is not only feasible for surgical data transport, but also transformative in addressing the challenges of real-time, multimodal communication in remote surgery systems. Future research should focus on transitioning from simulation to practical implementation, including the development of hardware prototypes, validation in clinical settings, and integration with advanced technologies, such as 6G networks and AI-assisted decision support. Additionally, exploring the synergy between OIL and spectral multiplexing techniques, including wavelength division and subcarrier multiplexing, may further improve system scalability and spectral efficiency, positioning OIL as a cornerstone of a robust and adaptive biomedical communication infrastructure.

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