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Review

Recent Advances in Optical Injection Locking for Visible Light Communication Applications

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Abstract: The introduction of visible light communication (VLC) technology could increase the capacity of existing wireless communication systems towards 6G networks. In practice, VLC can make good use of lighting system infrastructures to transmit data using light fidelity (Li-Fi). The use of semiconductor light sources, including light-emitting diodes (LEDs) and laser diodes (LDs) are essential to VLC technology because these devices are energy-efficient and have long lifespans. To achieve high-speed VLC links, various technologies have been utilized, including injection locking. Optical injection locking (OIL) is an optical frequency and phase synchronization technique that has been implemented in semiconductor laser systems for performance enhancement. High-performance optoelectronic devices with narrow linewidth, wide tunable emission, large modulation bandwidth and high data transmission rates are desired for advanced VLC. Thus, the features of OIL could be promising for building high-performance VLC systems. In this paper, we present a comprehensive review of the implementation of the injection-locking technique in optical communication systems. The enhancement of characteristics through OIL is elucidated. The applications of OIL in VLC systems are discussed. The prospects of OIL for future VLC systems are evaluated.

Keywords: optical injection locking; visible light communication; laser diode; Li-Fi

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1. Introduction

Visible light communication (VLC) is a high-speed communication technique utilizing an unlicensed frequency range of 400–800 THz [1]. Since the development of semiconductor lasers and optical fibers, optical communication systems have been widely used in our daily life [2]. With rapid growing wireless data demands, there is currently a push for environmentally friendly, high-speed and sustainable wireless communication methods in both indoor and outdoor environments. VLC can offer both lighting and communication at the same time, which could be a highly promising complement to conventional radio frequency (RF) wireless communication for high-speed local area networks in future 6G systems [3].

Optical injection locking (OIL) is an optical frequency and phase synchronization technique that is based on photon–photon interactions. Different from multiple section laser diodes, in which lights from different sections affect each other, there is one laser affecting the other in OIL. The latter may occur when external lights are shone into laser cavities [4]. The schematic diagrams of typical OIL schemes are illustrated in Figure 1. A typical external OIL configuration consists of master lasers and slave lasers. The master light can be injected into the slave laser and the output light can be blocked from the master laser via a circulator. A self-injection-locking configuration consists of a reflector through which light can be partially fed back. It is typically well acknowledged that the OIL technique is able to improve the device performance of semiconductor lasers, and there has been a mass of studies with regard to using the technique to build high-quality systems for telecommunication applications [5].

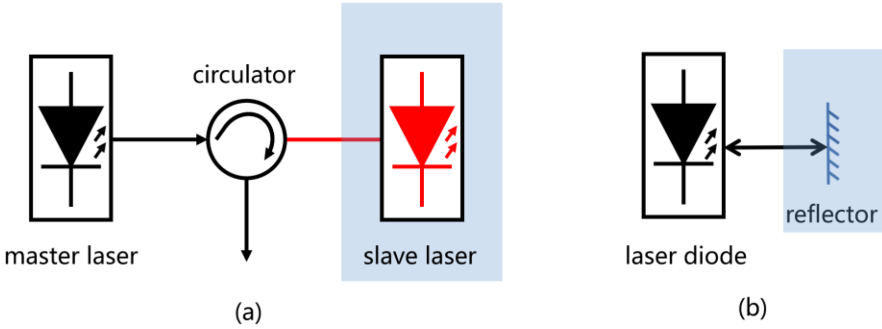

Figure 1. Schematic diagrams of the OIL technique. (**a**) External OIL configuration consists of master lasers and slave lasers. The master light can be injected into the slave laser and the output light can be blocked from the master laser via a circulator. (**b**) Self-injection-locking configuration consists of a reflector through which light can be partially fed back.

In VLC systems, OIL lasers are recently utilized as high-quality light sources for high-bitrate data links. Studies have demonstrated the enhancement effects of the OIL technique on the characteristics of different devices in the visible color regime. Additionally, the application of OIL is now demonstrated in various VLC systems, such as free-space VLC, visible light-based optical fiber communication and underwater wireless optical communication (UWOC).

In this paper, we review the recent advances in OIL and its applications in VLC. Firstly, the enhancement effects of OIL on the characteristics of different semiconductor optoelectronic devices are discussed, which could play vital roles in the future development of VLC systems and LiFi networks. Then, the most recent applications of OIL in VLC systems, including the implementation of OIL in fiber communication and UWOC systems, are analyzed. Finally, we elucidate the expected future trends in high-quality devices, such as ultranarrow-linewidth lasers for coherent optical communication.

2. Applications of Optical Injection Locking (OIL) in Different Fields

In the 1980s, following the development of semiconductor lasers for telecom applications, scientists actively began investigating the applications of OIL in optical communication systems [4]. Over the course of its history, the OIL technique has been utilized in many fields, prior to the development of VLC systems.

OIL has been successfully applied in the infrared wavelength field. Research regarding the effects of OIL on the noise properties of mid-infrared quantum cascade lasers has produced results that indicate that locked slave lasers could operate under reduced-intensity noise levels compared with the free-running operation [6], thereby corroborating the characteristic enhancement ability of the injection-locking technique. This practical approach to achieving low-noise operation for quantum cascade lasers is critical for the majority of applications in gas sensing and absorption spectroscopy. In 2020, a 448 Gb/s four-level pulse amplitude modulation (PAM4) free-space optical communication system with a 600 m free-space link was constructed, which also utilized polarization multiplexing optical injection-locked vertical cavity surface-emitting lasers (VCSELs) [7]. The VCSELs were optically injected with light from distributed feedback (DFB) LDs via the combination of a three-port optical circulator and a polarization controller. The findings from the experiment demonstrated that four 1.55 μm VCSEL transmitters were sufficiently powerful for 448 Gb/s PAM4 signal transmission when using the OIL technique. Additionally, the utilization of an eight-mode self-injection-locked quantum dash laser diode (LD) and a Reed–Solomon encoding technique in a secure PAM4-based free-space optical communication system was presented [8], which could transmit 88 Gbps of data over 555 m optical free-space links.

Moreover, the OIL technique has also been implemented in the generation and transmission of microwave and mmWave signals. Recently, there have been several studies on the generation and transmission of microwave and mmWave signals using the OIL technique. For example, Zhang et al. presented a frequency-modulated microwave generation setup including one master laser and two slave lasers [9]. In such a system, slow and fast perturbations were used to study frequency-modulated and externally locked P1 dynamics. The frequency-modulated continuous-wave generation at 6 GHz was achieved using externally locked lasers, with a comb contrast of up to 42 dB.

In an all-optical Ka-band microwave long-distance dissemination system, which was based on an optoelectronic oscillator (OEO), a single tone with high spectrum purity and low phase noise was excited by an optical injection-locked OEO, thereby achieving the stable phase transmission of mmWave signals [10]. Additionally, self-injection-locked quantum dash LD comb source technology has been used to produce a tunable 50/75 GHz mmWave transmission system in the difficult 1610 nm area [11]. Examples of mmWave generation and transmission systems are shown in Figure 2.

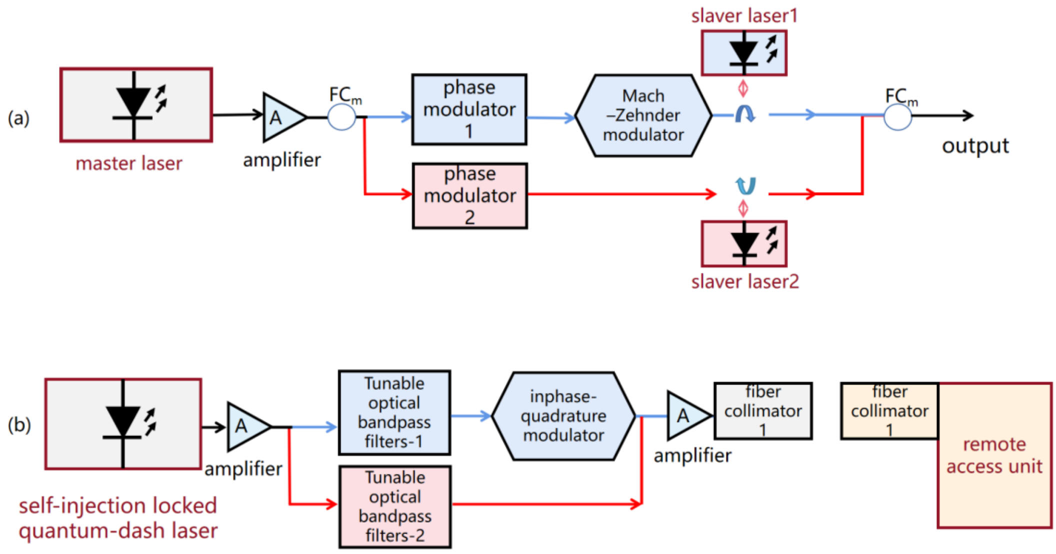

Figure 2. (**a**) The perturbed P1 dynamics of semiconductor lasers for frequency-modulated continuous-wave generation with external injection locking [8]; (**b**) A self-injection-locked quantum dash LD comb source, based on a 50/75 GHz mmWave transport system [11].

Furthermore, using a hybrid integrated self-injection-locking DFB laser, a gain-switched optical frequency comb source was proposed, which had eight pure continuous comb lines within 3 dB of the spectral envelope peak and a narrow linewidth of 615 kHz [12]. The carrier to noise ratio and the phase correlation between the comb lines were significantly improved by the self-injection-locking effect that was induced by the silicon nitride mirroring reflector, which could be promising for future radio over fiber and coherent optical communication.

In addition to the generation and transmission of microwaves and mmWaves as well as the production of frequency comb sources, self-injection-locked DFB LDs can be used for the high-sensitivity detection of acoustic emissions via fiber-coil Fabry–Pérot (F-P) interferometer sensors [13] and injection locking GaN blue LDs can be used for laser cooling and the trapping of ytterbium atoms in the field of physics [14].

Overall, OIL has been implemented in numerous applications over recent decades and now plays significant roles in various applications.

3. Enhancement Effects of OIL on the Characteristics of Different Devices

Since GaN-based devices have drawn significant attention for their application in VLC systems, we firstly examined the OIL in violet-blue-green light emitters. GaN-based LDs have demonstrated significantly higher modulation frequencies, greater power and better beam quality in comparison to GaN-based light-emitting diodes (LEDs). These features enable GaN LDs to produce long-distance transmission and open the door for the realization of emerging VLC applications. With the implementation of the OIL technique, the performance of GaN LDs has been further improved. Table 1 summarizes the enhancement effects of OIL on the characteristics of GaN LDs and the comparison with free running LDs.

Table 1. The enhancement effects of OIL on the characteristics of different devices [15–17].

Setup	Pros	Cons
Free-running blue F-P laser diodes	Simple structure	Relatively large emission spectrum linewidth
InGaN/GaN DFB LDs with gratings	Near-single-mode emission and a high side-mode suppression ratio	Fabrication of high-quality DFB grating is challenging
Littrow or Littman external cavity LD systems	A narrower linewidth and a high side-mode suppression ratio	System complexity (i.e., requires dielectric gratings or other wavelength filtering elements)
External cavity semiconductor LD systems	A satisfactory tuning range and high output power	Fine-tuning structure is required
Self-injection-locked LD systems	Good wavelength tunability and high optical power	Additional system complexity

In 2018, researchers from KFUPM and KAUST reported the application of self-injection locking in InGaN/GaN (blue/green) and InGaP/AlGaInP (red) visible light LD systems, in which the free-space optical feedback paths were accomplished using external mirrors [18]. They achieved significant increases of $\sim$57% (1.53–2.41 GHz) and $\sim$31% (1.72–2.26 GHz) in the modulation bandwidth and $\sim$9 (1.0–0.11 nm)- and $\sim$9 (0.63–0.07 nm)-fold reductions in the spectral linewidths of the green and blue lasers, respectively.

The following year, self-injection-locked green LDs using tunable dual-wavelength systems have been explored [19]. The self-injection-locking scheme was based on an external cavity configuration and utilized either highly or partially reflective mirrors. A tunable longitudinal mode spacing of 0.20–5.96 nm was accomplished, which corresponded to a calculated frequency difference of 0.22–6.51 THz. To further explore the systems, the same group employed the self-injection-locking technique for InGaN/GaN green LDs in an external cavity configuration with a partially reflective mirror using single- and multiwavelength laser systems [20]. The single-stage self-injection-locked laser system was for tunable laser and multiwavelength generation, while the two-stage self-injection-locked laser system was for near-single-wavelength generation. Figure 3 shows the narrow linewidth in single-mode, dual-mode and four-mode self-injection-locked green LDs at $\sim$525 nm and the two-stage self-injection-locking setup achieved a narrow locked-mode linewidth of $\sim$34 pm at 524.05 nm.

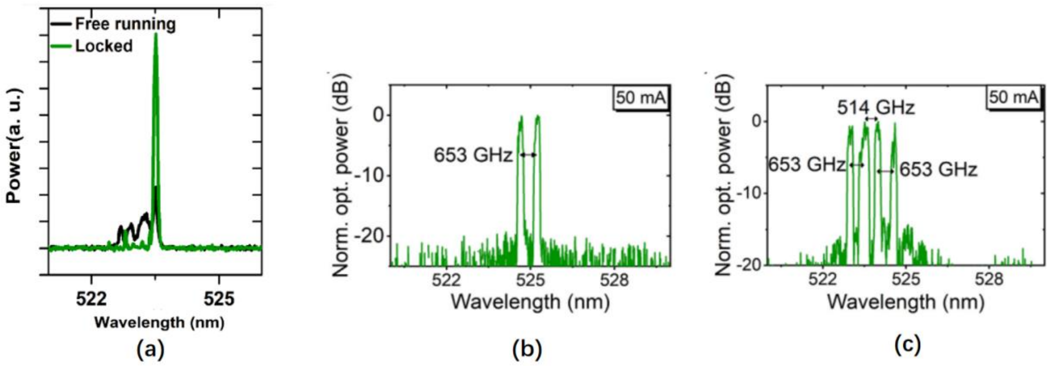

Figure 3. (**a**) The enhancement in the power of free-running (black) and self-injection-locked (green) systems for green LDs [18]; the normalized multiwavelength spectra of self-injection-locked external cavity systems with simultaneous (**b**) dual-and (**c**) four-mode generation, with an injection current (temperature) of 50 mA (40 °C) from a multiwavelength laser system [20].

Later in 2020, a prism-based self-injection-locked seamlessly tunable blue InGaN/GaN LD composite cavity system was presented [21]. The team achieved a clear main peak in the spectrum in contrast to the free-running one. Using an external cavity configuration and the self-injection-locking technique, the robust, simple and compact system achieved a significant enhancement in the wavelength-tuning window of up to 12.11 and 8 nm with ∼3 and 14.5 mW optical power via high-reflection and low-reflection configurations, respectively, at just above the threshold current. The measured output power at low, medium, and high injection currents for both high-reflection and low-reflection system configurations and the optical power of a free-running one are presented in Table 2.

Table 2. The measured output power at low, medium and high injection currents for both high-reflection and low-reflection system configurations as well as the optical power of a free-running LD system [21].

Injection Current (mA)	Working Power (mW)		
	Free Running System	High-Reflection System	Low-Reflection System
130	3.4	3	14
260	26	13	23
390	186	93	180

Additionally, in recent years, researchers have managed to utilize VCSELs as injected slave lasers and have found some interesting VCSEL characteristics in the infrared regime. These devices have two orthogonal polarizations of the fundamental transverse mode: the parallelly polarized mode and the orthogonally polarized mode. The mode competition means that one of the modes is the main mode and the other is its subsidiary. However, the situation can reverse under different conditions of the injection signals, which means that the polarizations can be switched by changing the intensity of injections or detuning frequencies [22]. Spikes can be generated by utilizing OIL in slave lasers, which can be further applied in optical spike neural networks. Lu et al. proposed an approach to generate neuron-like spikes for self-injection-locked VCSELs (~1.56 µm) using multifrequency switching [23]. A controllable spiking coding scheme that utilized switching was designed, which reached speeds of up to 1 Gbps experimentally. The affiliation of [24] used optical inputs extracted from digital images as signals that were injected into VCSELs (~1.30 µm), thus achieving all-optical binary convolution.

In summary, the typical implementation of OIL systems is based on packaged LDs and external cavities with reflective setups. These compact systems can obtain considerable decreases in linewidth and increases in output power and modulation bandwidth whilst maintaining a high quality of stability, which is embodied by a satisfactory side-mode suppression ratio (SMSR). Hence, OIL-based optical transmitters could function competently as vital light sources in a variety of other applications, and have shown great potential for implementation in high-bitrate VLC schemes.

4. Applications of OIL in Visible Light Communication Systems

4.1. Applications of OIL in Free-Space Visible Light Communication Systems

The adoption of the OIL approach in free-space VLC systems can improve the system performance in many distinct ways.

In 2013, a novel bidirectional lightwave transport system was proposed, which employed a phase modulation scheme and an optical injection-locked DFB LD as a duplex transceiver for passive optical networks [25]. The critical part of the OIL technique in that study was that it could be achieved when the frequency of the master laser (DFB LD1) was lower than that of the slave laser (DFB LD2), through which the system obtained a low bit error rate. In 2020, another bidirectional free-space optical communication system was built with a 600 m free-space transmission, which applied a phase modulation scheme and a remotely optical injection-locked DFB LD [26].

As well as DFB LDs, optical injection-locked VCSELs have also been deployed successfully. In 2015, a 10 m/25 Gbps Li-Fi transmission system was proposed, which was based on a two-stage optical injection-locked 680 nm VCSEL transmitter [27]. Compared to the free-running system (5.2 GHz), the two-stage optical injection-locked system achieved a pronounced increase in the 3 dB bandwidth of up to 26.2 GHz.

In 2020, a tunable external cavity self-injection-locked violet LD system was reported, which exhibited a continuous wavelength tunability of 5.15 nm (400.28–405.43 nm), with mean SMSR and linewidth values of $\sim$23 dB and $\sim$190 pm, respectively [28]. The salient setup of that system was a pellicle beam splitter with a 92:8% splitting ratio within the external cavity, which could transmit 92% of the optical power back to the front facet of the laser, thereby realizing high-quality external cavity self-injection locking.

In addition to the distinctive qualities of the various device categories, there are some differences between self-injection and external injection locking. In 2018, a team of researchers from KAUST launched an investigation into the performance enhancement effects of self-injection and external injection locking for high-bitrate VLC systems [29]. They discovered that $\sim$1.4- and $\sim$1.1-fold improvements in the modulation bandwidth and $\sim$6.5- and $\sim$3.2-fold reductions in the spectral linewidth were achieved using self-injection-locked blue and red LDs, respectively. The short external cavity self-injection-locked system also exhibited superior performance by a factor of 1.1–1.3 compared to the long cavity (26 cm) configuration. Conversely, the external injection system exhibited weak locking signatures but improved linewidths by a factor of $\sim$1.6–2.8, reaching as low as $\sim$70 and $\sim$87 pm for the blue and red LDs, respectively, while almost doubling the peak powers. A comparison of the characteristic enhancements of blue and red LDs in SIL and external optical injection cases is exhibited in Table 3.

Furthermore, two-stage injection has become more common nowadays. In 2022, a wavelength-division multiplexing visible laser light communication and white light ring network was successfully demonstrated this year, which achieved a 150 Gbit/s accumulative transmission rate at the central station, a 50 Gbit/s transmission rate at the optical node and 604 lux white light at the central station [30]. By utilizing red, green and blue LDs with the two-stage OIL and optoelectronic feedback technique, high-speed laser-based VLC links and white light illumination at the reading or writing level could be accomplished.

Overall, different OIL techniques, including self-injection, external injection and multi-stage injection, have been applied to enhance a diverse range of devices, with the primary goals of greater -3 dB modulation bandwidth improvements and enhanced data transmission capacities with high bitrates.

Table 3. Comparison of the characteristic enhancements of blue and red LDs in SIL and external optical injection cases [29].

Characteristic Enhancement Compared to Free-Running System	Working Power (mW)			
	Self-Injection-Locked System		External Optical Injection System	
	Blue (~450 nm)	Red (~650 nm)	Blue (~450 nm)	Red (~650 nm)
Peak power improvement (times)	∼2.8	∼1.7	∼1.7	∼1.4
Linewidth reduction (times)	∼6.4	∼1.65	∼2.8	∼1.6

4.2. The Applications of OIL in Fiber Optical Communication Systems

Hybrid radio over fiber- and laser-based VLC systems could support the integration of fiber backbones and indoor networks to provide integrated broadband services, including Internet and telecommunication services.

In 2014, a phase modulation-based bidirectional hybrid radio over fiber- and VCSEL-based fiber optical communication systems (680 nm/red) was proposed and demonstrated, which employed optical injection-locked VCSEL-based PM in intensity modulation (IM) converters and optical interleavers [31]. The key setup was the PM–IM converters, which consisted of an optical circulator and a VCSEL. As the VCSEL was self-injection-locked, the upper sideband (+1 sideband) of the phase-modulated optical signal was amplified, while the lower sideband (−1 sideband) stayed unchanged; therefore, the OIL enhanced the intensity of the upper sideband. Ultimately, the bit error rate and clear-eye diagram achieved good transmission performance over a 40 km single-mode fiber (SMF) transmission and a 12 m free-space laser-based VLC link with red LD.

The following year, another research team successfully applied the two-stage OIL and optoelectronic feedback technique in a bidirectional lightwave transport system, which was based on fiber-visible laser light communication integration [32]. Light was successfully modulated directly for cable television, 16-quadrature amplitude modulation (QAM) and 16-QAM–orthogonal frequency division multiplexing signals. The system made use of optical injection locked DFB LDs within infrared regime (LD2 and LD3). The optical output of DFB LD2 was injected into DFB LD3 via an optical circulator. Not only was the channel capacity doubled, but good carrier-to-noise ratio, composite second-order distortion, composite triple beat distortion and qualified bit error rate values were also obtained over a 40 km SMF, a 1.43 km photonic crystal fiber and a 6 m free-space laser-based VLC transport system.

The two aforementioned bidirectional lightwave transport systems show that fiber–laser-based VLC systems could have significant potential for providing integrated broadband services, such as cable television, Internet and telecommunication services, via optical fibers and indoor free-space networks.

4.3. The Applications of OIL in Underwater Wireless Optical Communication (UWOC)

Underwater wireless communication plays a crucial role in marine activities, such as environmental monitoring, underwater exploration and scientific data collection. In recent years, UWOC systems have emerged as promising wireless carrier candidates for signal transmission systems in acrimonious, uncharted and turbulent water environments, such as seas. Due to their characteristics of high output power and considerable stability, optical injection-locked sources have demonstrated the tendency to cope well with optical signal propagation issues that occur in UWOC systems, such as strong water turbulence and significant signal attenuation. Figure 4 displays several recent applications of OIL in UWOC systems.

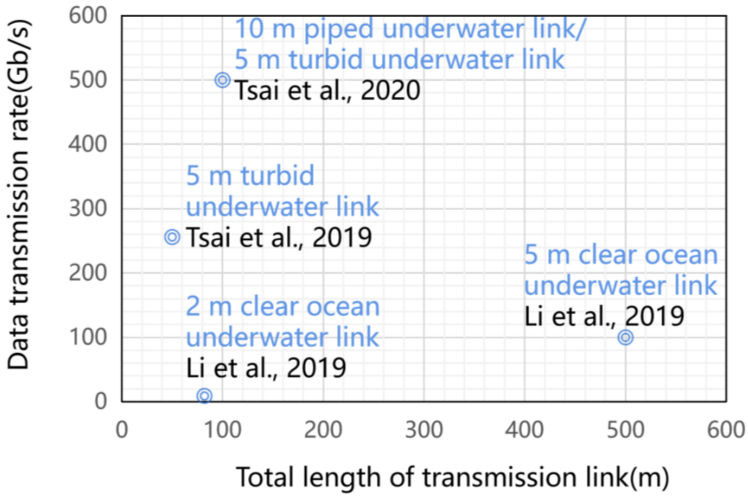

Figure 4. Recent applications of OIL in hybrid free space—UWOC systems. The total length of transmission link (x-axis) contains both underwater portion (blue) and free-space counterpart [33–36].

In 2020, Ming Chi University of Technology established a 500 Gb/s PAM4 free-space optical UWOC convergent system for 100 m free-space transmission using either a 10 m piped underwater link or a 5 m turbid underwater link, which integrated PAM4 modulation with a five-wavelength polarization multiplexing scheme [33]. The critical part of that scheme was the utilization of two-stage OIL and optoelectronic feedback on the LDs. With the two-stage OIL and optoelectronic feedback technique, the −3 dB bandwidths were enhanced by ∼10 times compared to a free-running counterpart.

Similarly, another wavelength-division multiplexing PAM4 free-space optical integrated FSO UWOC system was proposed, which had a channel capacity of 100 Gb/s [34]. The system applied 405 nm blue–violet light LDs and 1.7 GHz 450 nm blue light LDs via the two-stage OIL and optoelectronic feedback technique, which were adequately adopted for 100 Gb/s PAM4 signal transmission using a 500 m free-space transmission with a 5 m clear ocean underwater link. Apart from the critical deployment of the two-stage OIL and optoelectronic feedback technique, doublet lenses in the FSO, laser beam reducers and transmissive spatial light modulators were also crucial elements that helped the system to achieve a low bit error rate.

To sum up, with the development of signal modulation and multistage injection locking techniques, practical and high-speed underwater optical wireless links, as shown in Figure 5, which could enable high data rate transmission, are just around the corner.

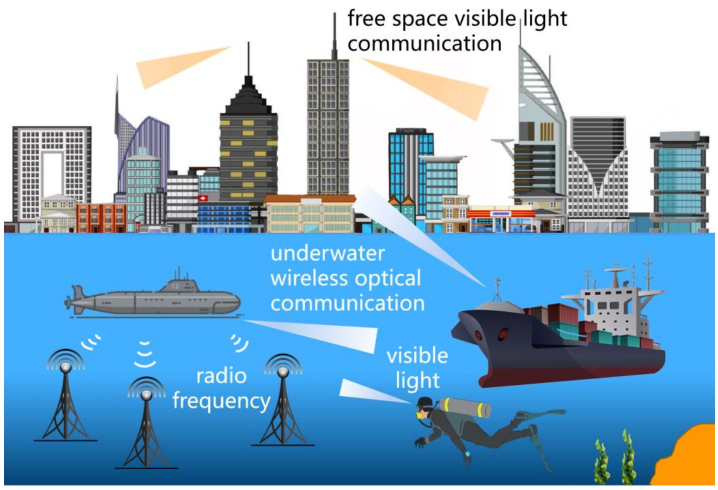

Figure 5. OIL in different VLC applications.

5. Future Trends of OIL in VLC

Current researchers have focused on the key materials and devices, high-speed system technology, networking technology, and the applications of VLC. Towards high performance VLC links, the utilization of OIL technology in VLC systems calls for the development of compact, low cost and manufacturable OIL transmitter on a chip, enabling the on-chip integration of light emitters. The form factor of the existing OIL setups is still large when comparing with commercial transceivers in telecommunication applications. The eventual deployment of VLC systems in practical applications, such as in mobile devices and underwater wireless networks, requires the further scaling down of the device size when OIL is used in VLC transmitter. This could be performed by designing a copackaging scheme of optical components with diode lasers, or on-chip integration of light emitters with passive optical devices. Moreover, future work on developing a high-optical-efficiency OIL is an important research topic. There are various sources of loss in current OIL system that can lead to reduced energy efficiency. Since achieving a low power consumption is one of the key objectives in 6G, the study of OIL technology with high optical efficiency in a visible color regime is another essential point that further research can lay emphasis on.

In addition, coherent optical communication is a promising approach for long-distance VLC, in which the requirements for narrow-linewidth and high-power devices are more demanding. Feedback mechanisms such as OIL can stabilize the frequency and reduce the spectral linewidth of the devices. Thus, future coherent VLC could be developed based on the high-performance visible light emitters using OIL.

Looking beyond, investigations into the implementation of OIL could lead to more advanced high-performance devices and VLC systems in the future.

6. Conclusions

In this review, we elucidated recent advances in the OIL technique, particularly in the visible light color regime. The ability of the OIL approach to enhance the performance of optoelectronic devices is well recognized, and there is a vast array of existing research that has used the technology for optical communication applications. We presented research concerning the enhancement effects of OIL on the characteristics of different devices, which has demonstrated satisfactory increases in output power as well as high SMSR values. We also examined studies on the application of OIL in various VLC systems. The two-stage OIL and optoelectronic feedback technique has turned out to be a salient and practical approach in these intricate real-life situations, thanks to its state-of-art characteristics of high output power and considerable stability.

VLC is an emerging technology that has a bright future, and the development of OIL in VLC could function as a helpful road map for developing greater and more effective VLC networks and systems.

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