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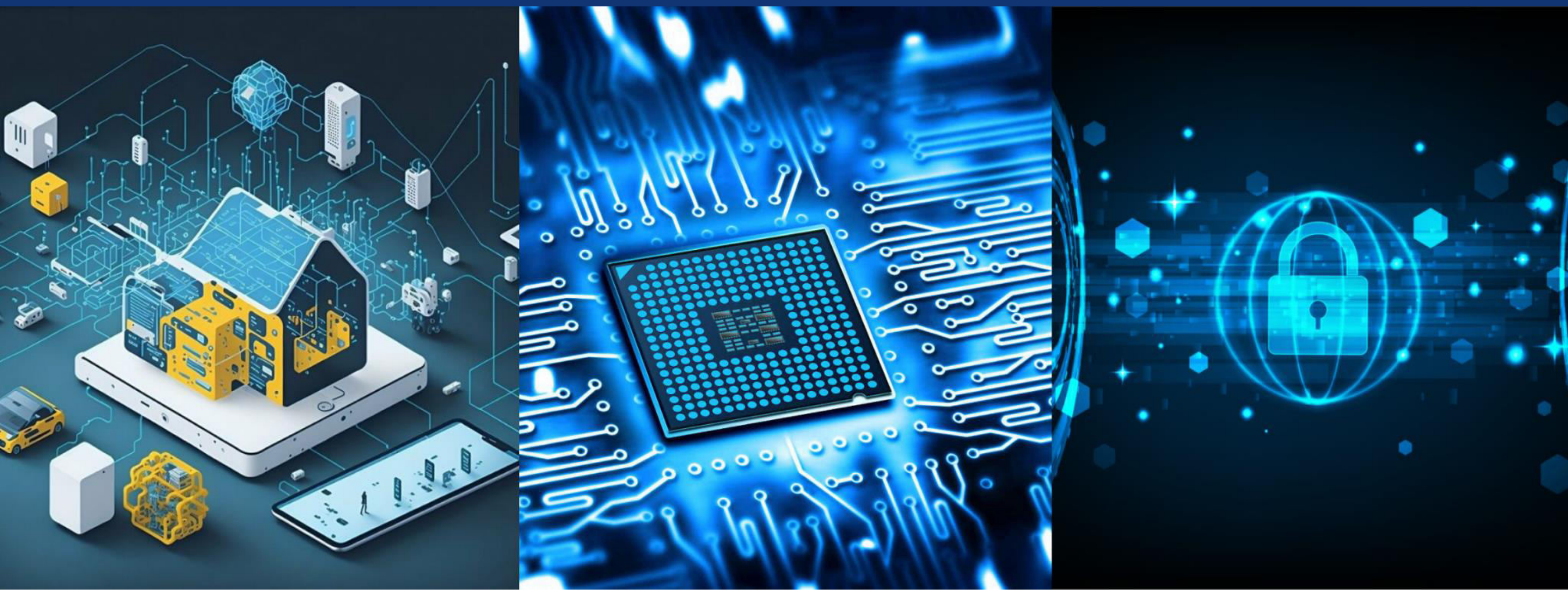

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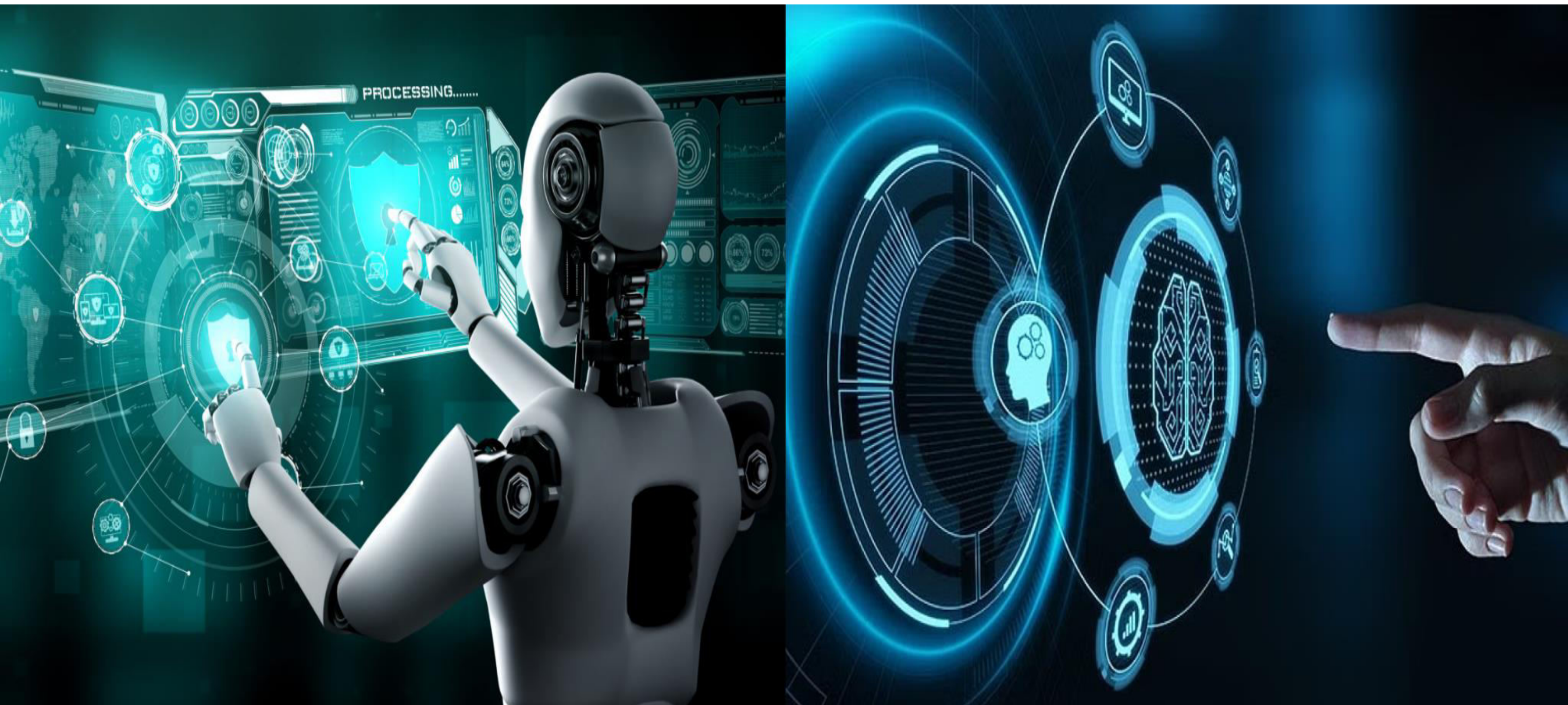

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Fiber-Based Energy Harvesting From ASE in Optical Systems

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ABSTRACT: Energy harvesting over fiber (EHoF) utilizing amplified spontaneous emission (ASE) from erbium-doped fiber amplifiers (EDFAs) presents a novel approach for powering optical sensing and communication systems. This technique leverages the excess energy emitted during the amplification process, enabling the efficient collection and conversion of light energy into usable electrical power. By integrating EHoF into existing fiber-optic networks, passive devices can be energized without the need for external power sources, enhancing the sustainability and functionality of these systems. The research explores the potential applications of EHoF in various domains, including distributed sensing and communication, highlighting its advantages in reducing operational costs and improving system reliability. Furthermore, the study addresses the challenges associated with energy conversion efficiency and the optimization of fiber-optic components to maximize energy capture. Overall, this work contributes to the advancement of energy-efficient technologies in optical systems, paving the way for innovative solutions in the field of telecommunications and environmental monitoring.

I. INTRODUCTION

In many applications in land, space, and undersea environments, optical sensing and communication systems are essential. However, there are a number of difficulties in integrating these technologies, especially when it comes to energy management and sustainability. In order to provide a wide range of services and functions for connected users and devices in both terrestrial and underwater contexts, the optical communication research and development community is striving to fulfill the growing need for transmission capacity. In the context of smart cities, for example, the creation of next-generation networks (NGNs) requires the deployment of sophisticated optical communication systems that enable high-speed data transfer via optical fibers and free-space optical (FSO) links. The community is also working to improve sensing and monitoring capabilities by developing extremely sensitive, distributed, real-time. The integration of communication and sensing functionalities into a single grid or network is the vision for the perfect n etwork of the future in smart cities.This makes it possible to reuse hardware and spectrum for both sensing and commu nication tasks, enabling the construction of dual-purpose green networks on reasonably priced technology.

Managing interference between communication and sensing signals, assigning available bandwidth, and controlling po wer consumption and distribution within the system are the key problems of combining optical communication and sen sing into a single system.

The latter is especially important in harsh or remote environments, such as underwater habitats. Underwater optical communication, also known as underwater optical wireless communication (UOWC) or maritime optical fiber cables, has gained increasing attention due to its numerous applications in scientific research, environmental monitoring, offshore energy exploration, and defense activities. The objective of establishing an equivalent Internet of Things (IoT) beneath the seas, commonly referred to as the Internet of Underwater Things, has led to the integration of various capabilities and services, such as communication and sensing, within the same marine grid. Making ensuring the communication/sensing systems are energy sustainable is one of the most significant problems of this integration, given the harsh or remote conditions of underwater locations.

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II. ENERGY HARVESTING OVER FIBER

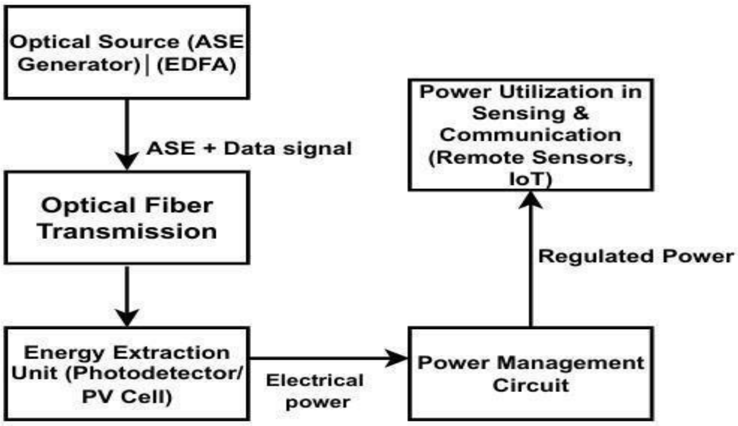

Fig 1. Block diagram of Energy Harvesting Over Fiber From ASE in Optical sensing

This block diagram represents a system for energy harvesting over optical fiber using an Amplified Spontaneous Emission (ASE) source or an Erbium-Doped Fiber Amplifier (EDFA).

1. **Optical Source**: The process starts with an optical source, such as an ASE generatoror EDFA, which generates both amplified optical signals and data signals.
2. **Optical Fiber Transmission**: The ASE signal, along with the data signal ,is transmitted through an optical fiber.
3. **Energy Extraction Unit**: At the receiving end, a photodetector or photovoltaic (PV) cell extracts electrical power from the transmitted optical signal.
4. **Power Management Circuit**: The extracted electrical power is then processed and regulated by a power management circuit to ensure a stable and usable power supply.
5. **Power Utilization**: The regulated power is then used for remote sensing and communication applications, such as powering IoT devices or remote sensors.

III. WORKING PRINCIPLE

Energy harvesting over optical fiber using Amplified Spontaneous Emission (ASE) exploits residual optical power, typically from erbium-doped fiber amplifiers (EDFAs), to provide electrical energy to remote devices. ASE is generated in EDFAs due to spontaneous emission that gets amplified along with signal light. While ASE is often considered noise in communication systems, its consistent broadband power can be used as an energy source.

In this technique, unused ASE power propagates along the fiber and is tapped at the remote sensor or communication node. A photodetector or photovoltaic power converter (PPC) at the receiving end converts the optical ASE into electrical power. This electrical power can support low-energy operations such as sensor measurements, signal processing, and data transmission. The method eliminates the need for batteries or separate power lines in distributed optical networks, which is particularly valuable in inaccessible or hazardous environments.

The dual use of the fiber infrastructure for both data and energy transmission enhances system efficiency and reduces deployment complexity. Moreover, the approach is compatible with standard fiber-optic components, making it suitable for integration into existing networks. Overall, ASE-based energy harvesting presents a promising solution for powering remote optical sensing and communication devices.

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IV. ENERGY HARVESTING OVER FIBER IN A FIBER-OPTIC COMMUNICATION SYSTEM

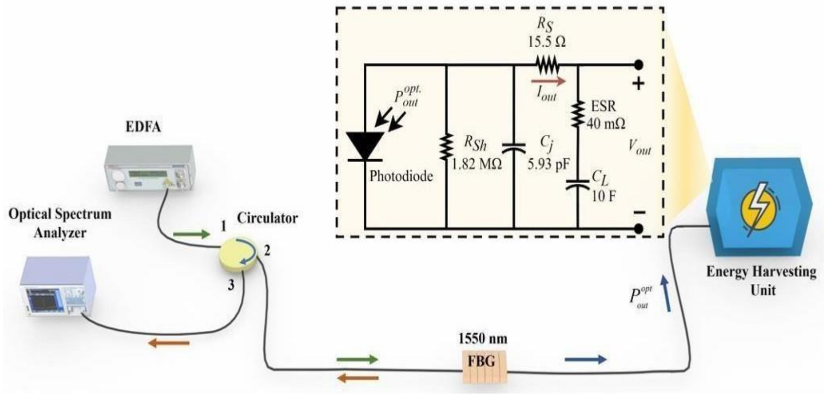

Fig 2. Schematic design of the energy harvesting system

The diagram illustrates a setup for energy harvesting over optical fiber using Amplified Spontaneous Emission (ASE) in conjunction with optical sensing. An Erbium-Doped Fiber Amplifier (EDFA) generates ASE, which is directed by a circulator into the optical fiber. The circulator allows light to flow in one direction—from the EDFA through port 1 to port 2—preventing signal interference. A Fiber Bragg Grating (FBG) is placed along the fiber to reflect a specific wavelength (e.g., 1550 nm), enabling sensing applications or wavelength filtering.

The remaining ASE power, denoted as PoptoutP_{opt}^{out}Poptout, continues to the energy harvesting unit. Inside this unit, a photodiode converts the incoming optical power into electrical current. The equivalent circuit of the photodiode includes series resistance (RSR_SRS), shunt resistance (RShR_{Sh}RSh), junction capacitance (CjC_jCj), and a parallel capacitor (CLC_LCL) representing the energy storage element. The output current (IoutI_{out}Iout) charges the capacitor, providing a voltage output (VoutV_{out}Vout) for powering low-power electronics.

This configuration efficiently utilizes residual ASE light for dual purposes: enabling sensing via FBG and delivering electrical energy to remote units. It demonstrates a compact, fiber-integrated solution suitable for powering distributed sensor nodes without requiring external power sources or batteries.

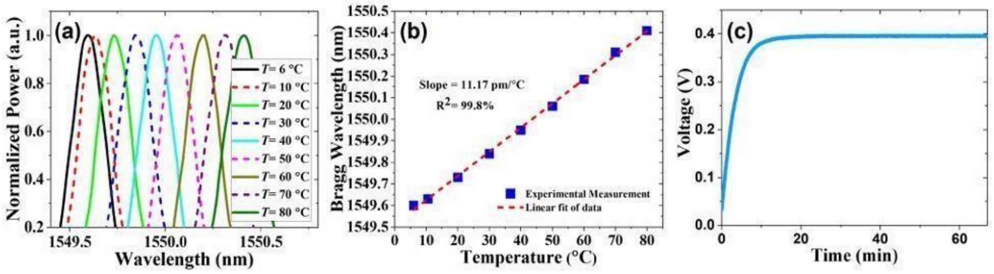

Fig 3

(a) Normalized reflected spectra from the FBG at different temperature values.
(b) Linear fitting of the Bragg wavelength versus temperature variation.
(c) Charging curve of the super capacitor using the EH unit located at the distal end of the optical fiber.
The provided figure demonstrates the performance of an energy harvesting and sensing system based on Amplified Spontaneous Emission (ASE) over optical fiber.

In part (a), normalized reflection spectra from a Fiber Bragg Grating (FBG) are shown at various temperatures ranging from 6°C to 80°C. As temperature increases, the Bragg wavelength shifts toward longer wavelengths (redshift), confirming the FBG's temperature sensitivity. This shift is crucial for sensing applications, allowing the FBG to act as a passive temperature sensor in the optical system.

Part (b) presents a linear relationship between the Bragg wavelength and temperature, with a slope of 11.17 pm/°C and a high correlation (R^2 = 99.8%). This confirms the FBG's precise and consistent thermal response, enabling accurate temperature measurements when integrated with the ASE-based energy delivery system.

Part (c) shows the voltage output of the energy harvesting circuit over time. As ASE light is converted into electrical energy by the photodiode and stored in a capacitor, the voltage rises and stabilizes around 0.4 V in under 20 minutes. This demonstrates that sufficient electrical power can be harvested from ASE light to support low-power sensing operations.

Together, these plots validate the dual-use concept of ASE for both energy harvesting and environmental sensing over standard optical fiber infrastructure.

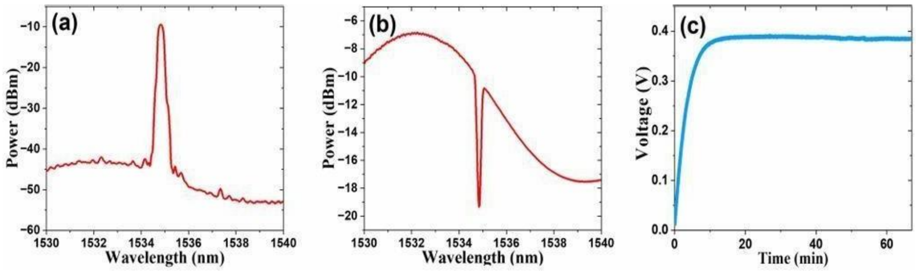

Fig 4: Illustrates the performance of an optical energy harvesting and sensing system utilizing Amplified Spontaneous Emission (ASE) in fiber-optic networks

Graph (a) displays the power spectrum of the ASE source after amplification. A distinct peak around 1534 nm indicates the dominant wavelength component, while the surrounding lower power levels represent the broadband nature of ASE. This spectral profile is characteristic of an erbium-doped fiber amplifier (EDFA) used as the ASE source, delivering both sensing and energy-harvesting capabilities.

Graph (b) shows the spectral response after filtering or interaction with a sensing element, likely a Fiber Bragg Grating (FBG). The dip at the central wavelength (~1534 nm) signifies wavelength-selective reflection or absorption, confirming the interaction between ASE light and the sensing device. This interaction enables simultaneous sensing (e.g., temperature or strain) by tracking spectral shifts.

Graph (c) presents the voltage output of the energy harvesting unit over time. As ASE light reaches a photodiode-based circuit, optical power is converted into electrical energy. The voltage rises rapidly and stabilizes near 0.4 V within 10–15 minutes, indicating efficient energy conversion and storage suitable for powering low-power electronics.
Together, these graphs confirm the feasibility of using ASE for dual-purpose fiber-optic sensing and energy harvesting in remote or embedded systems.

V. CONCLUSION

Energy harvesting over optical fiber using Amplified Spontaneous Emission (ASE) offers a promising solution for powering distributed sensing and communication devices, especially in remote or hard-to-access environments. By utilizing the residual ASE power from erbium-doped fiber amplifiers, this approach provides a continuous and stable optical energy source that can be converted into electrical power through photodiodes or photovoltaic converters. This eliminates the dependence on batteries or dedicated power lines, significantly enhancing system reliability and reducing maintenance. The integration of Fiber Bragg Gratings (FBGs) into the system enables accurate environmental sensing, such as temperature monitoring, by exploiting the wavelength shift characteristics of FBGs. Experimental results demonstrate the linear response of FBGs to temperature variations, along with efficient voltage generation through energy harvesting circuits, confirming the practicality of this dual-function system.Overall, this technique leverages existing fiber infrastructure to deliver both data and energy, reducing complexity and cost. Its compatibility with standard optical components and ability to support real-time sensing make it an attractive approach for next-generation fiber-optic sensor networks. The successful demonstration of this concept paves the way for scalable, self-sustained sensor systems ideal for industrial monitoring, smart cities, and environmental surveillance.

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VI. FUTURE ENHANCEMENT

Future advancements in energy harvesting over fiber from ASE in optical sensing and communication systems can focus on several key areas to improve efficiency, scalability, and real-world applicability. One major enhancement is the optimization of optical-to-electrical conversion efficiency by developing highly sensitive photodetectors and photovoltaic (PV) cells capable of extracting maximum power from ASE while minimizing losses. Additionally, the integration of machine learning (ML) and artificial intelligence (AI) techniques can enable adaptive power management, optimizing energy distribution based on network demand and environmental conditions. Another critical area for future research is the hybridization of energy sources, where ASE energy harvesting is combined with other optical power transmission techniques such as laser-based wireless power transfer or radio frequency (RF) energy harvesting to enhance power availability. Furthermore, the use of advanced optical amplifiers and multi-wavelength ASE sources can significantly improve energy harvesting potential while maintaining efficient data transmission. Enhancing ASE noise management techniques through advanced filtering, modulation schemes, and error correction algorithms can further ensure reliable communication while extracting energy.

Additionally, the development of ultra-low-power sensors and improved photovoltaic converters will further increase the feasibility of self-sustaining optical networks. Expanding this technology to support 5G and future 6G networks, as well as applications in remote monitoring and the Internet of Things (IoT), will broaden its impact. Overcoming challenges related to signal integrity, loss minimization, and seamless integration with existing infrastructure will be key to making ASE-based energy harvesting a mainstream solution for energy-efficient and sustainable optical communication systems.

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