CURRENT AND EMERGING TECHNOLOGIES IN THE FIELD OF UNDERWATER WIRELESS COMMUNICATION- A BRIEF REVIEW ON OPTICAL AND ACOUSTIC TECHNOLOGIES

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Course Report on The Basics of Marine Information

Current and Emerging Technologies in the Field of Underwater Wireless Communication- A Brief Review on Optical and Acoustic Technologies

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I declare that the assignment here submitted is original except for source material explicitly acknowledged, and that the same or related material has not been previously submitted for another course. I also acknowledge that I am aware of University policy and regulations on honesty in academic work, and of the disciplinary guidelines and procedures applicable to breaches of such policy and regulations.

Signature: 

Date: 7th June 2020

Summary

Underwater wireless technologies are fast developing and their relevance to ocean engineering and remote sensing cannot be overemphasized. The principles that govern these devices range from radio frequency to optics and acoustics. In this report I highlight some technolo0gies that have been discovered or invented and applied to the area of underwater wireless communication. Herein, their mode of operation, merits and demerits are highlighted. It is seen that the acoustic and optical wireless communication technologies are most applicable to the field with acoustic technologies most applied to long range underwater wireless communication

1. Introduction

The Marine environment has a variety of varying features that make it different from the terrestrial where standard wireless communication systems are employed. In the marine environment, several factors may influence communications. Factors like salt concentration, temperature, pressure, light penetration, winds, and their effects on waves. Amidst all these challenges, wireless communications still play a significant role in efficient underwater systems. There are three major categories of technologies available for marine wireless transmissions [1,2]

The first technology is radio-frequency (RF) communication or electromagnetic technology, which passes a high amount of data at a short-range with just a little Doppler Effect. At lower frequencies, such as at extremely low and very low-frequency ranges (ELF and VLF, respectively), the electromagnetic-wave attenuation can be considered small enough to allow for reliable communications over long distances up to several kilometers. This frequency ranges from 3 Hz to 3 kHz. Unfortunately, 3 kHz to 30 kHz are not wide enough for data transmissions at high data rates. The propagation of the RF signal is influenced by environmental conditions, such as temperature and salinity, dependent on frequency [1,3]

The second technology is the optical transmission, preferably in blue-green wavelength, which relies on a direct line-of-sight. The primary difference between RF and optical propagation in seawater is the behavior of the medium. Water behaves as a conductor for RF and as a dielectric for optical signals [2,3]. This phenomenon finds its reliance on the plasma frequency, whose value determines the frequency range for which water behaves as a conductor or as a dielectric—seawater changes from conductor to dielectric at frequencies around 250 GHz. The propagation distance of optical signals is dependent on the frequency range. The understanding that the blue-green optical window has lower propagation attenuation has been used to improve blue-green sources and detectors in the past decades. Considering the effects of environmental conditions, the two main water properties relevant to optical transmission are the spectral absorption coefficient and the spectral volume scattering function [1,3]

The third technology, which is the most used underwater technology, is acoustic communication. As earlier stated, both RF and optical transmissions have significant limitations regarding the propagation range under minimum signal attenuation [4]. RF is severely impacted by strong attenuation, leading to a small propagation distance, and optical technologies depend on the water clarity or turbidity. As such, acoustic communication is an alternative technology to reach higher distances, currently being the dominant technology for wireless underwater communications. Acoustic technology is the one that allows the most extended range of communication. Still, it achieves low throughput. It is highly impaired by Doppler effects and is affected by a significant delay spread that leads to severe interference [1,2,4]. This report aims to provide a brief overview of the current and emerging principles and technologies currently employed in underwater communication. Herein, their mode of operation, merits and demerits are highlighted. RF was not reviewed in this report because of low applicability in the field, in sections 2and 3 the principles of the technologies currently employed in the field of optical and acoustic wireless communications are discussed [1,2]

2. Optical Transduction and Receiving Technologies

Transducers used in underwater optical communications have different requirements depending on their functionality. Either as sensors at the receiver end or as actuators at the transmitter end. Transducers designed to produce optical signals from electrical signals are composed of an optical source, optical projection system, and beam steering. In contrast, transducers for sensing optical signals and converting them into electrical signals are made up of collection optics and detectors [6,7]. A schematic is shown in Fig.1

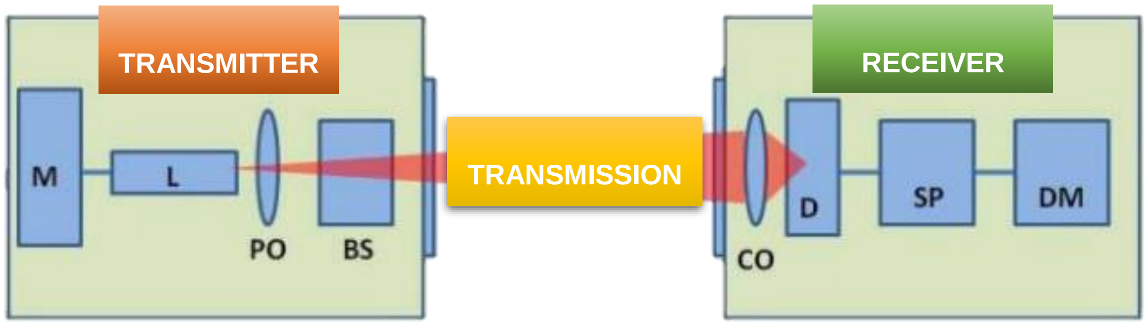

Fig. 1: Conceptual components of a typical underwater optical communications system. The transmitter is composed of a Modulator (M), Laser (L) Projection Optics (PO), and Beam Steering (BS) systems. The receiver is made of Collection Optics (CO), Detector (D), Signal Processing (SP), and Demodulator (DM) systems. [7]

2.1 Transmitters

Two optical carrier technologies operate in this power and bandwidth regime: lasers and Light Emitting Diodes (LEDs) [8]

Technologies of Transmitters

A. Light Emitting Diodes (LEDs):

A light-emitting diode (LED) is a semiconductor light source that produces light when current flows through it [7,9]. Emitted electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons [10]. The P-N junction is an integral part of its design, as shown in Fig.2. The energy needed for electrons to cross the insulated gap of the semiconductor determines the hue of the light, which corresponds to the photons energy [11， 12]. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device. [7]. LEDs have a high electrical-to-optical conversion efficiency of approximately 10% and operate at wavelengths ranging from 375–520 nm and a power output of a few watts and can support data rates of up to 1 megabit per second. The chances of improving the output power of these devices to several watts exist [7]. However, such a power increase leads to higher junction capacitance, which results in slower transient response. Recent research has been aimed at building high-speed arrays of smaller LEDs generating 1–10 milliwatts per device [3]. A critical problem of using LED to enable underwater optical communications is their wide spectral bandwidth of about 25–40 nm full-width at half maximum. The spectral filter's width is driven by the spectral bandwidth of the transmitter, which in turn makes it very difficult to filter out solar background noise. As a result, LEDs appear to be useful only for short-range underwater optical communications such as building an underwater sensor network. However, LEDs are not a viable option for long-range underwater interactions, such as linking underwater vehicles with satellites [7].

(a)

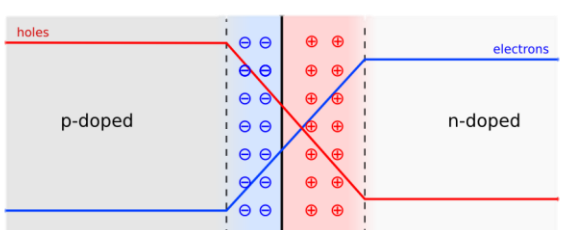

Fig. 2: p–n junction [11,12]

B. Light Amplification by Stimulated Emission of Radiation (LASER)

I. Argon-Ion LASERS

Argon ion laser utilizes ionized gas argon as its lasing media. Similar to other gas lasers, Argon ion lasers have a sealed cavity housing the laser medium and mirrors forming a resonator as shown in Fig. 3. As opposed to helium-neon lasers, the energy level transitions that add to laser action come from ions. The argon-ion laser was invented at the Hughes Aircraft Company in 1964 by William Bridges [13]. It is one of the families of ion lasers that utilize a noble gas as the active medium. Argon-ion lasers emit 13 wavelengths through the visible and ultraviolet spectra. *However, wavelengths in the blue-green region of the visible spectrum are the most commonly used* [3,7]. These wavelengths can potentially be used in underwater communications because seawater is quite transparent in this range of wavelengths. The argon-ion laser can generate multi-watt outputs at a variety of blue-green wavelengths, *but they are incredibly inefficient (less than 0.1% electrical-to-optical conversion efficiency)* [7]

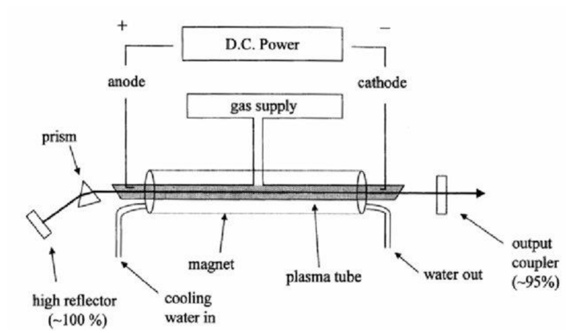

Fig. 3: Schematic of an argon ion laser [14]

II. Diode-Pumped Solid-State (DPSS) LASERS

An alternative technique is the use of green Diode-Pumped Solid-State (DPSS) lasers, which utilize nonlinear optics in a Potassium Titanyl Phosphate (KTP) crystal to generate *a frequency-doubled output of near-infrared*. Diode-pumped solid-state (DPSS) lasers are solid-state lasers made by pumping a solid gain medium, with a laser diode. Green DPSS lasers have an efficiency of about 20% and emit 532 nm light. In theory, a green DPSS laser could have an overall ability of up to 48%. Blue DPSS lasers generate light in the 473 nm regimes, thanks to the use of a beta barium borate (BBO) or lithium triborate (LBO) crystal [8]. *Unfortunately, these lasers are relatively weak because of the lower gain of the materials, and the overall efficiency is only about 3–5%. In recent years,* Bismuth Triborate (BiBO) crystals have been proposed to increase the efficiency of DPSS lasers. And perhaps more famous for underwater applications, BiBO crystals are not hygroscopic. That is, the crystal will not degrade due to the presence of moisture in the environment [7,*15]*

III. Indium Gallium Nitride (InGaN) LASERS

As its name suggests, InGaN lasers *use gallium nitride (GaN) and indium nitride (InN) semiconductors, producing blue light without the need to perform frequency doubling*. For example, the lasers developed for high-density optical storage on blu-ray discs operate at 405 nm with an output power of a few hundreds of milliwatt. Longer wavelength lasers are also available in the range between 450–470 nm, but their optical output is considerably weaker at a few tens of milliwatt. Also, InGaN lasers are characterized by a short rise and fall times of less than a nanosecond. This property is due to the short carrier relaxation time in the active laser region. Furthermore*, InGaN lasers have a narrow* *spectral bandwidth of less than 1 nm*. On the other hand, these devices are far more expensive than LEDs (a factor of 100 or more), and they are often prone to over-current damage [3,8]. A schematic showing its working principle is shown in Fig 4.

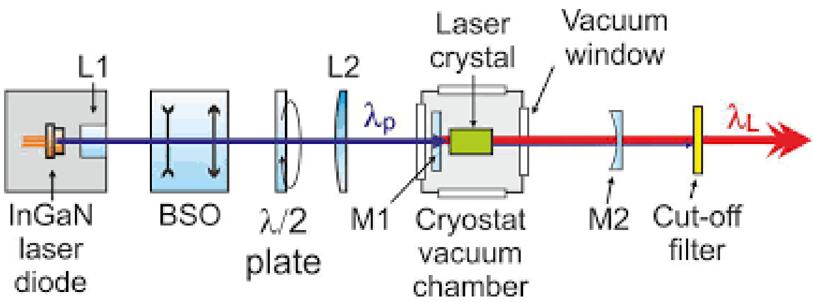

Fig. 4: Schematic of an InGaN Lasers [16]

IV. Tunable LASERS

Frequencies corresponding to minimum attenuation of an optical channel changes in different ocean waters, this critical frequency strongly depends on the concentration of scattering particles. Consequently, it is essential to have tunable lasers able to continuously change their emission frequency to adapt to the changing environment dynamically [3,8]. The first step in designing a tunable laser is a laser medium with a broad gain profile. Such is the case of the dye laser, which was discovered by Sorokin and Lankard, and by Schafer in 1966. However, to date remains a challenge to design a high-power tunable laser in the green-blue region using semiconductor lasers. The main obstacles in this direction are the lack of both a highly reflective semiconductor distributed Bragg reflectors and a compact and efficient pump source [7]

V. LASER Modulators

It is possible to use Q-switching, also known as giant pulse formation or Q-spoiling, to generate modulated laser pulses. Also known as the 'giant pulse formation technique,' this technique allows the generation of light pulses with extremely high peak power. The pulses are produced through the modulation of the laser internal cavity loss. This is done in practice by introducing a variable attenuator inside the laser's optical resonator. However, Q-switching can only be used for meager data rates (Hz to kHz) propagating at the most extended ranges allowable by seawater attenuation (a few hundred meters). In order to get higher data rates, it is necessary to use an external optical modulator coupled to a mode-locked or continuous-wave laser. This technique increases the data bandwidth of the laser and gives more choices for its hardware implementation [7]

2.2 Receivers

A good optical receiver has a high signal-to-noise ratio while using the least energy per bit, and this means that the receiver needs to have the largest possible collecting area to detect incoming photons. However, the etendue will play an important role in the design of an optical detector. The etendue or optical throughput is often given by the product "AΩ "between the area of the detector "A" and the solid angle subtended by the detector "Ω." The etendue is invariant in a lossless optical system, i.e.,

$A1\Omega1 = A2\ \Omega\ 2$

It is closely related to the invariance of irradiance and the conservation of energy. Therefore, a perfect optical system will always produce an image with the same etendue as the source. 7

Technologies of Receivers

A. Semiconductor Photo-Sensors

Photo-detectors, also called photo sensors, are sensors of light or other electromagnetic radiation. [7]. A photodetector has a p–n junction that converts light photons into the current. The absorbed photons make electron-hole pairs in the depletion region. Semiconductor photo sensors include PIN photodiodes and avalanche photodiodes (APD) The first type is characterized by the fast response time, but they have no internal gain. On the other hand, avalanche photodiodes have a slower response time, but they have internal gains of nearly a factor of 100 [7]. Figure 5 shows the principle of photo detection.

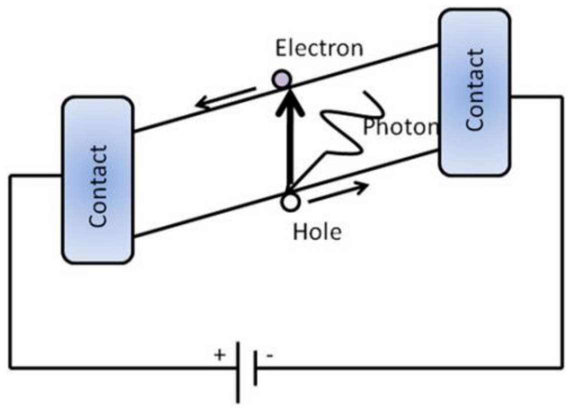

Fig. 5: Principle of photo detection in a semiconductor. A photon generates an electron–hole pair which carries current under an electrical bias [12].

B. Photo-Multiplier Tubes

Photo-multiplier tubes (PMTs) as shown in Fig. 6 are vacuum tubes that contain a photocathode, which transforms a photon into an electron via the photoelectric effect, and an electron-multiplying tube that increases the number of electrons by means of secondary emission processes. PMTs are characterized by high gain, low noise, high-frequency response, and large collection areas. These sensors are extremely sensitive in the ultraviolet through the near-infrared regime. On the other hand, PMTs are more extensive, more expensive, and more challenging to ruggedize than semiconductor devices. Also, PMTs have higher power requirements. Furthermore, PMTs may be severely damaged if exposed to very bright light. [7]

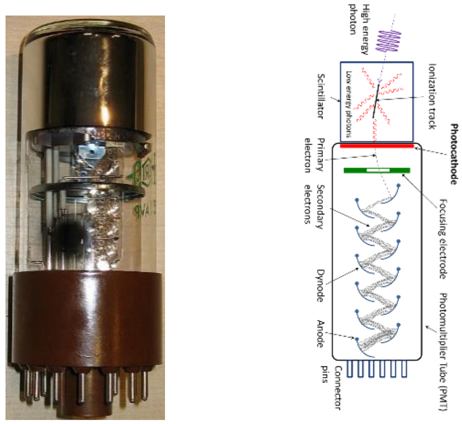

Fig. 6: Schematic of A Photomultiplier tube [17]

C. Biologically-Inspired Quantum Photo-Sensors (BQP)

The field of quantum sensing deals with the design and engineering of quantum sources (e.g., entangled) and quantum measurements that are able to beat the performance of any classical strategy in a number of technological applications. This can be done considering photonic systems or solid state systems. One of the technical goals of the Quantum photo sensor research program is to design novel kinds of photo sensors. These sensors are made of new materials that attempt to synthesize the highly efficient quantum transport phenomena observed in photosynthesis. It is expected that these materials will allow the construction of photodetectors. Quantum efficiency of nearly 90% in the 460–480 nm range will surpass the current capabilities provided by Avalanche Photodetectors and PIN (un-doped intrinsic semiconductor) photodetectors. One such candidate involves the use of J-aggregates [7]. These are molecules that self-assemble and exhibit quantum transport over hundreds of chromophores at room temperature. As a consequence, J-aggregates appear to closely mimic the behavior of chlorosome antenna in green sulfur bacteria. [7]. In BQP self-aggregation is a key principle to achieve optimized photo detection, as illustrated in Fig. 7

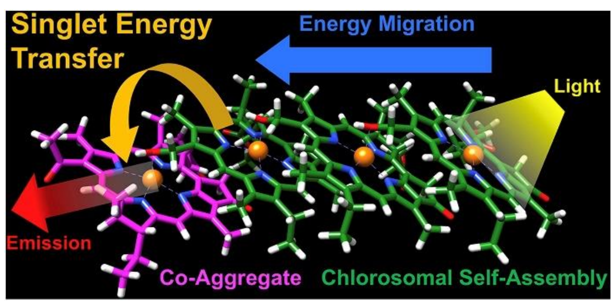

Fig. 7: Schematic drawing of supramolecular co-aggregates (a) and their energy transferring pathways [18]

3. Acoustic Modem Technologies

An acoustic modem is employed to send data underwater, just as telephone modems are used to transmit data over landlines. An acoustic modem changes digital data into underwater sound signals. These signals are received by another acoustic modem and converted back into digital data [6,5] Fig.8. Acoustic modems can be used for marine telemetry, ROV and AUV command and control, diver communications, underwater monitoring and data logging, and other applications requiring underwater wireless communications. Acoustic transducers are major components of acoustic modems. They are the component in the modem that convert electrical signals into sound (transmitter) or sound into electrical signals (receiver) [19]. Transmitters are called sources or projectors, and receivers are called hydrophones. These devices are designed for underwater environments and can be attached to floating objects (e.g., boat or buoy) or can be moored [5,6]. The most prevalent types of transducers are piezoelectric and magnetostrictive.

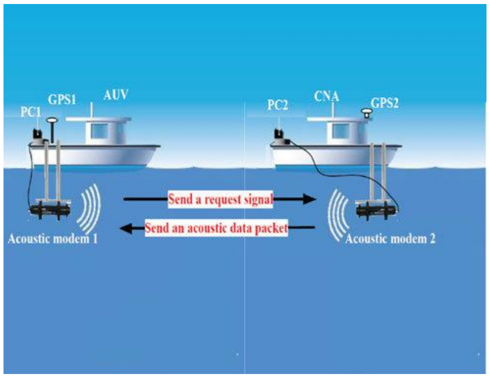

Fig. 8: The diagram of underwater acoustic communication between the AUV (Autonomous underwater vehicles) and CAN (communication and navigation aid). [20]

Piezoelectric Acoustic Underwater Transducers

Three types of materials are reviewed here. Piezoelectric ceramics, composites, and polymers, these are currently extensively used in underwater acoustic communication. Piezoelectric materials respond to stress/force my generating electricity and deforms when an electric current is passed through them of their temperature altered. Figure 8 illustrates the perovskite structure using BaTiO3 as an example. When the temperature is above the Curie point of the material, the structure can be described as a cubic cell. The smaller cation (B, titanium in this case) is in the body center, the larger cation (A, barium in this case) is on the corners, and the oxygen's (O) are in the centers of all six faces. When the temperature is lowered below the Curie point, the titanium ion moves away from the center of the cell along one of the two orthogonal axes connecting the titanium and the oxygen atoms, elongating the cell in the corresponding direction and resulting in a spontaneous polarization [21] Fig.9.

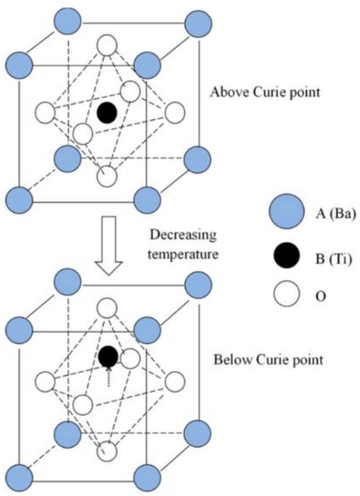

Fig. 9: Schematic of the perovskite structure (ABO3) with BaTiO3 as an example

A. PZT Ceramics

Piezoelectric ceramics are widely used in marine acoustic technologies. PZT has been the most critical family in piezoelectric ceramics because of its useful piezoelectric features, high Curie points, and a range of properties that small changes in composition can offer. According to the United States military standard, piezoelectric ceramics are categorized into six different categories, namely Navy Type 1 through Navy Type 6. Navy Type 1 are Isovalent-additive modified PZTs applicable to medium- or high-drive sonar applications, and heat generation is a primary concern because the transducer usually operates at its resonance [21]. For applications in which stability under high electric drive is most critical and where compromise of electromechanical performance is acceptable, acceptor modified PZT ceramics (Navy Type 3) are the materials of choice. Because donor-modified PZTs have higher charge sensitivity at the expense of higher mechanical and dielectric loss, they are classified as Type 2 materials. These are suitable for passive transducer applications such as hydrophones but not for active acoustic radiating applications. Navy Type 4 piezoelectric ceramics are modified BaTiO3 compositions with lower piezoelectric activity and a lower Curie temperature than any of the PZT ceramics. They are usually not used in transducers. Navy Type 6 ceramics are similar to those of Navy Type 2 but with enhanced piezoelectric activity, higher dielectric constant, and lower Curie temperatures. Type 5 is an intermediate type between Navy Type 2 and Navy Type 6. In addition to these Navy types, other custom formulations of PZT are commercially available for special transducer applications [19,21]

B. Piezoelectric Polymers

Piezoelectric ceramics and single crystals offer excellent piezoelectric activity because of their strong ferroelectric properties. After PZT was discovered, PZT ceramics became widely used in underwater transducers because they provide a great compromise between manufacturing cost and performance. Single crystals are used in the applications where ultra-high sensitivity and acoustic power are needed. However, both of these materials have characteristics that are not ideal for specific underwater transducer applications [21]

The first is high acoustic impedance, which is defined as the product of the material density and the sound velocity in the material because of their high masses and elastic moduli. The typical acoustic impedance of piezoelectric ceramics and single crystals is higher than 30 MRayls [106g/(m2s)], whereas that of water is only 1.5 MRayls. Such a large acoustic impedance mismatch causes a significant reflection of the acoustic signal at the interface between the material and water [21,22]. Therefore, for underwater applications, acoustic matching layers are required for piezoelectric ceramics and single crystals. Second is their low hydrostatic piezoelectric response. In hydrophone applications where acoustic energy is converted into an electric signal, the piezoelectric voltage constant 'g' of the piezoelectric material directly relates to the hydrophone sensitivity. It expresses the electric field generated in the material per unit of mechanical stress applied. Piezoelectric polymers excel in applications where high acoustic impedance, low hydrostatic piezoelectric response, and flexibility are significant design constraints. Their low density and elastic constants translate into much lower acoustic impedance (merely two to six times that of water), thus offering much better acoustic matching with water. They also possess a much better hydrostatic-mode response and are much more flexible than ceramics and single crystals [21]

C. Piezoelectric Composites

Piezoelectric ceramics and single crystals, because of their high acoustic impedance, low hydrostatic piezoelectric coefficients, and lack of flexibility, are not optimum for underwater transducer applications [21-22]. On the other hand, polymers have acoustic impedances very close to that of water, and they are very flexible. However, their piezoelectric performance is inferior to that of ceramics and single crystals. A single-phase material that possesses both the merits offered by piezoelectric ceramics/single crystals and piezoelectric polymers simply does not exist. Thus, before piezoelectric composites, compromises were required in underwater transducer designs. In 1978, Newnham introduced the concept of composites "connectivity" in piezoelectric and pyroelectric ceramic and then started to apply the idea to piezoelectric–polymer composites in the 1980s. By structurally combining a piezoelectric ceramic and a polymer with specific connectivity, the resulting composite material can successfully integrate the best of both worlds. Connectivity defines the way in which the two end members (the piezoelectric ceramic and the polymer) connect in the composite. The convention is that the first digit defines how the active ceramic (the piezoelectric) is connected and the second how the passive phase (the polymer) is connected. For example, a 0-3 composite is fabricated by dispersing isolated piezoelectric ceramic particles (hence “0” dimensional) in a polymer matrix (hence “3” dimensional). A 1-3 composite is an array of piezoelectric ceramic rods embedded in a polymer with electrodes at the rod ends as shown in Fig.10 [21].

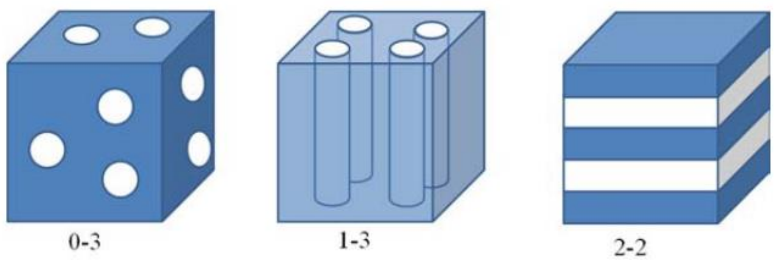

Fig. 10: Three typical connectivity patterns of diphasic piezoelectric composites used in underwater acoustic transducers.

D. Magnetostrictive Acoustic Transducers

Magnetostrictive materials convert magnetic energy to mechanical energy and vice versa. When a magnetostrictive material is magnetized, it exhibits a change in length per unit length. Conversely, if an external force is applied and strain is produced in a magnetostrictive article, the magnetic state of the material will change. This coupling between the magnetic and mechanical modes of magnetostrictive material results in a transduction capability that is applied for actuation and sensing purposes [23]

4. Conclusion

Underwater wireless communication technologies have been briefly introduced. Emerging technologies such as the Biologically-Inspired Quantum Photo-Sensors (BQP) provide opportunities to continually push the bounds of sensing technologies. Piezoelectric technologies provide opportunities to remotely sense our environment with a certain degree of confidence. In the future, piezoelectricity might be integrated with sensors in such a way as to harvest energy, continuously power the device while carrying out its primary objective.

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