Chapter 4

Optical Biotelemetry

Koichi Shimizu

ABSTRACT

The usefulness of biotelemetry (remote measurement of biological information) has been recognized in clinical medicine and animal sciences. In biotelemetry, the radio wave has been commonly used as a transmission medium. To answer many new demands for biotelemetry and to overcome various problems of radio telemetry, a technological method called optical biotelemetry has been developed. Using light as a transmission medium, the bandwidth for signal transmission is greatly increased and many EMI problems can be solved. Technical considerations required to realize the optical biotelemetry were presented. On the devices for optical biotelemetry, the wavelength of light, light sources, light detecting elements and the measures for optical noises were discussed. On data transmission, analogue and digital communication, modulation methods, intelligent transmission and multiplexing methods were discussed. To develop an optical biotelemetry technique, we need to know the characteristics of light propagation. The optical characteristics of body surface tissue and the distribution of indirect light in a room were discussed for transcutaneous telemetry and ambulatory telemetry using indirect light, respectively. Two techniques were proposed for multi-channel optical biotelemetry. They were the applications of a pulse-burst method and the spread spectrum method. As concrete examples of optical biotelemetry, some applications of this method to practical use are presented. They are the transcutaneous ECG telemetry, non-contact measurement of body surface displacement, ambulatory telemetry,

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multi-channel biotelemetry and data transmission between medical equipments. With its promising potential, it is expected that the optical biotelemetry opens new possibilities for further development of biotelemetry.

1. INTRODUCTION

Biotelemetry is defined as the measurement of biological signals from a remote place using a communication measure. In the history of the development of biomedical engineering, there were significant successes attained by applying engineering principles to clinical medicine. Biotelemetry is one of the typical examples of such a success, or the application of a telemetry technique to a biomedical measurement. From the first stage of the development of biomedical engineering, the biotelemetry technique has been applied in many areas of medicine. For instance, there have been different kinds of ECG transmission. Clinical applications include an ambulatory ECG measurement in an examination room, a centralized ECG monitoring in ICU, remote area transmission in telemedicine, etc. In research fields there have been well-known examples such as the radio capsule to measure various parameters in a digestive tract and the ECG/EMG measurement in sports medicine and in rehabilitation medicine.[1,2]

In biotelemetry we transmit the measured signal to a remote place by means of a medium for communication. A radio wave is a typical example of the medium. Since it has been used widely, people naturally think of it as radio telemetry when they say ‘biotelemetry’. The use of different media for data-transmission has been attempted, i.e. light and ultrasound. The feasibility and the usefulness of optical biotelemetry have been suggested early.[3,4] However, few studies have followed them. It is one of the reasons that optical technology has not matured to support the new development of optical biotelemetry. For example, a high-power transmitter and a sensitive detector could not be made portable. Recently optical technology has been advancing greatly, and now we have had a reliable laser diode and photo diode in our hand. The background of new progress of optical biotelemetry has been maturing.

Figure 1 shows the fundamental principle of optical biotelemetry. Based on the telemetry principle, we can separate the data-acquisition part from the data processing/display part by means of communication. By this separation we can expect the following merits of biotelemetry.

1) We can make the data acquisition part very small and light. This makes the measurement possible with minimal perturbation on the object or the subject. The ambulatory measurement is a typical example.

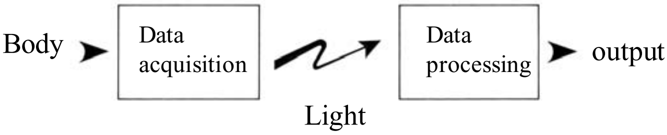


Figure 1. Basic principle of optical biotelemetry.

2) We can measure the signal in an environment which is not easily accessible, such as inside the body, deep in water and space.
3) We can monitor many subjects for a long period of time in the centralized system, such as an ICU.

Moreover, by use of light we can expect the following advantages over the conventional radio telemetry.

#1 We can achieve the wide-band signal transmission relatively easily. This corresponds to the possibility of information transmission with a good frequency characteristic or a high-speed temporal response. In another view, it indicates the possibility of high-speed large-capacity transmission of information.
#2 We can control the electromagnetic interference much easier than we can with radio telemetry. The signal light of the optical telemetry does not give interference to other instruments and does not receive interference from them. The shielding and securing safety can be done relatively easily.
#3 The legal restriction to use light for communication is not as strict as the radio wave.

There are of course some disadvantages with the optical biotelemetry. They are for example, the vulnerability to optical noises and the inability to reach the position out of the line of sight. However, they are not serious and can be overcome by technical measures which are discussed in the following sections.

The significances of the above advantages in biotelemetry are as follows. #1 means the improvement of the telemetry function itself over radio telemetry. It increases the practical value of the telemetry technique. With the wide-band transmission channel, we can use various intelligent techniques in the data-transmission. The significance of this advantage over radio telemetry is increasing with the progress of intelligent communication techniques. #2 is important for the serious problems of electromagnetic interference in a hospital. In a clinical environment, there are many sources of electromagnetic noise, such as an electric scalpel (radio knife, acusector), microwave hyperthermia and many devices with built-in microcomputers. Thus the telemetry system should not receive interference from them. Moreover, in a clinical environment, delicate equipments have increased such as life-support systems and centralized patient-monitoring systems. The trouble and malfunction of these system result in serious problems. Therefore, there are strict requirements to prevent a telemetry system from interfering with these systems. #3 becomes an important merit in the practical use of the telemetry system in a clinical environment and in field works.

As mentioned above, optical biotelemetry is a new technique with abundant potential. However the basic technology has not been sufficiently established compared with the radio telemetry. This chapter deals with the outline of the basic technologies necessary to use optical biotelemetry in practice. The common topics to radio telemetry such as the topics of electrodes and batteries are excluded. As concrete examples, some of the optical biotelemetry systems we have developed are introduced.

2. BASIC OPTICAL TECHNOLOGY FOR OPTICAL TELEMETRY

Optical biotelemetry is an integrated technology which consists of basic technologies such as optics, communication, biosignal measurement, and information processing. In the following sections, these basic technologies necessary for optical biotelemetry are outlined.

2.1. Selection of Wavelength

To design an optical biotelemetry system, the wavelength of optical communication has to be selected. Any wavelength of light, or ultraviolet-visible-infrared range, can be used for optical telemetry in principle. However, with ultraviolet light, the adverse effect on our health becomes a problem in a prolonged use. As for visible light, there may be a psychological effect on the subject. Further, in this wavelength, there are many sources of optical noise such as indoor lighting. With infrared light particularly of 700–1200 nm wavelength, such problems are few. Moreover, in this wavelength, the optical absorption of body tissue is relatively low, and we can expect high optical transmission through our body. Figure 2 shows the absorption spectra of the major constituents of a human body. In the ranges less than 700 nm and more than 1200 nm, the absorption of hemoglobin and water are predominant, respectively. Furthermore, this wavelength range has been used in optical fiber communication, and there are many kinds of sources and detectors available.

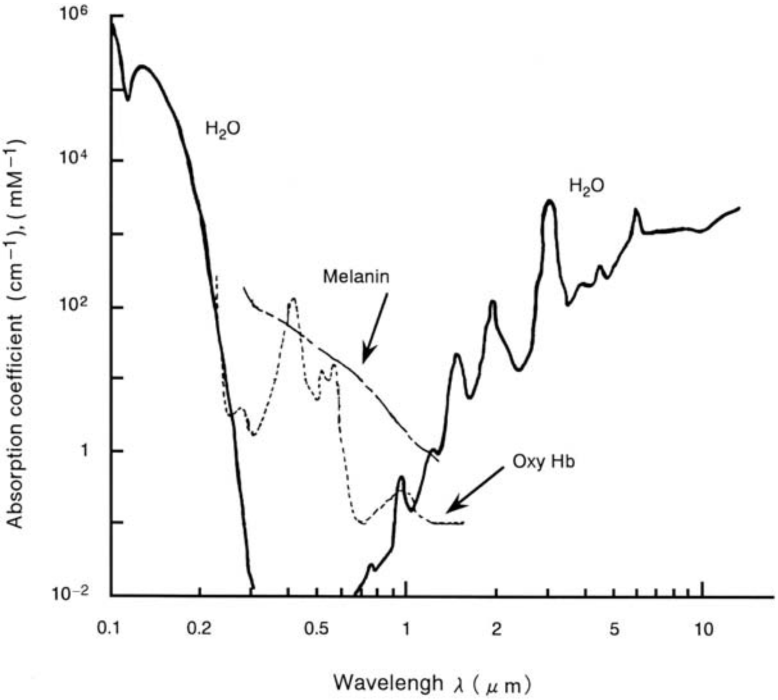


Figure 2. Absorption spectra of major constituents of human body.

2.2. Light Source

A basic part of the optical signal transmission consists of a light source and a photo-receiver. As a light source, a light emitting diode (LED) and a laser diode (LD) are used, generally. As semiconductor elements, they are small, light weight, operable with low voltage and with low power consumption. With each element, direct modulation is possible, as well. If we compared them, each has different merits in practical use. LED is generally inexpensive and easy to handle. LD is superior in monochromaticity, coherency and a response speed. These merits of LD become important in optical communication through an optical fiber and in the case of high frequency modulation (more than several hundreds MHz). However, these features are not necessarily required for the transmission of general biosignals such as an ECG (frequency range of 0-several hundreds Hz). In such a case, LED's are often used.

When a large amount of optical power is required like in the optical communication using indirect scattered light, many elements of the light source are used. To drive many elements simultaneously, we can connect the elements in series or in parallel at the last stage of a driver circuit. They are shown in Figures 3 (a) and 3(b). Since a current-source drive is a standard with LED, the series connection is preferable to make the light emission of each LED uniform. Moreover, the composite capacitance of LED becomes small in the series connection. It is advantageous when high-speed operation such as a pulse-wave drive is required. However in the series connection, the number of elements (n) cannot exceed a certain limit. This is because the forward voltage V_F times n cannot exceed the power-supply voltage V_{CC}. As a result, we often need to divide the series connection into some parallel connections of short series elements (Figure 3 (c)).

2.3. Light Detecting Elements

A light detector forms the front end of the receiver of data-transmission. As the detector, a photo diode (PD), a photo transistor (PTr), an avalanche photo diode (APD) or a photo-multiplier (PMT) is commonly used. To detect a low-level-light at a phton counting level, the detector with an internal gain such as APD and PMT are used. PTr is used as a

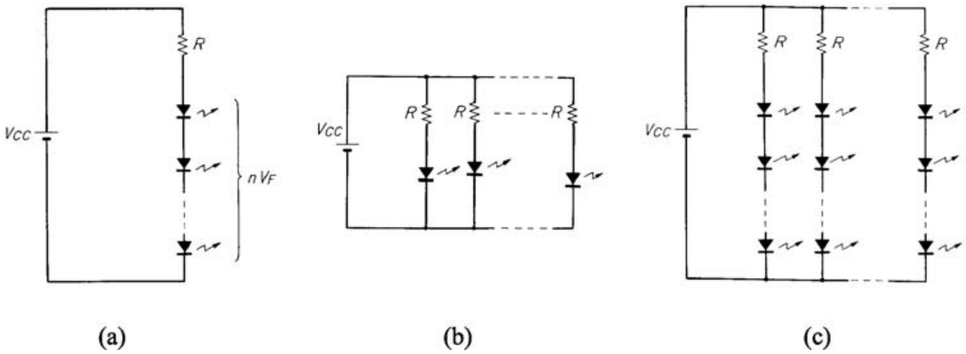


Figure 3. Driving of multiple light emitting elements: (a) series, (b) parallel, (c) mixed, V_{CC}: source voltage, n: number of elements, V_F: forward voltage.

photo-receiving part of such a composite element as a photo-coupler and a photo-interrupter. In optical biotelemetry, the PD is often used since it is easy to handle. Particularly a PIN photodiode can meet the requirement of high-speed operation (typically from some tens of MHz to some GHz) relatively easily. It is suitable for a wide-band digital data transmission system.

In optical telemetry, it is necessary to amplify the electric signal from PD and to process the signal in a wave-shaping circuit and a demodulation circuit. When high-sensitivity and high-speed operation are required, the performance of the whole receiver is often dominated by the first part of the receiver circuits rather than by the detector element itself. To solve this problem, new devices have been developed recently. They include the PD with built-in operational amplifiers as a preamplifier, and the OPIC (optical IC) which is an IC with a photodiode and signal processing circuit integrated on a single chip of IC.

2.4. Measures for Optical Noises

In practical application of biotelemetry, the measurement is particularly vulnerable to the foreign noise coming into the communication channel. Since optical telemetry uses light as the carrier of communication, it shows extremely high resistance to electromagnetic noise. However, it is certainly vulnerable to the effects of optical noise. To deal with this problem, two kinds of filters, or an optical filter and an electric filter are used. The noise source with the largest effect in a room is a fluorescent lamp. As shown in Figure 4, the major emission spectrum of a fluorescent lamp lies between 400–700 nm. Therefore we can greatly suppress its effect using the optical filter, which cuts the wavelength range shorter than a visible light. The filter is often called a black filter.

As for sunlight and the light of an incandescent lamp, we can eliminate a considerable part of the effect using an electronic filter. After the photo-electric conversion at the photo-detector, the frequency component of these lights is well-defined. They are either very low-frequency near DC or some harmonics of the power-line frequency (50 or 60 Hz). Thus, it is not difficult to eliminate them by an electronic filter. However, we have to be careful not to saturate the photo-detector in any case.

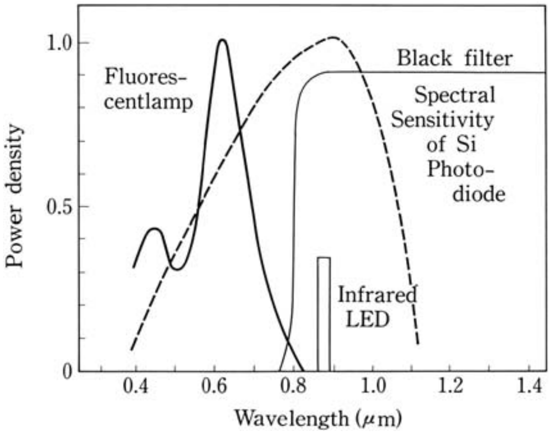


Figure 4. Spectral characteristics of optical elements.

3. BASIC COMMUNICATION TECHNOLOGY FOR OPTICAL TELEMETRY

Figure 5 shows a basic flow of the signal transmission in optical biotelemetry. A special consideration to optical biotelemetry is necessary in the part from the modulator to the demodulator. In this section, the communication technology concerning this part is described.

3.1. Analog/Digital Transmission

Most of the biomedical information can be measured as an analogue signal. A conventional medical telemeter such as an ECG telemeter transmits analogue information in an analogue signal. In analogue transmission the electronic circuit is generally simple. It is suitable to make the telemeter small in size and low in power consumption.

With the progress of digital technology and components, digital techniques have often been used in biotelemetry recently. It may sound meaningless to convert the analogue biological signal into a digital one and then back into an analogue signal at the receiving end. However, the advantage of the digital signal transmission is particularly significant in the intelligent data transmission as mentioned in a later section.

3.2. Modulation Method

In the conventional radio telemetry, a continuous wave modulation (AM, FM, etc.) and a pulse wave modulation (PPM, PIM, PCM, etc.) were used.[5] Commonly, in optical biotelemetry, we first modulate the electric signal using these modulation methods, and then modulate the light intensity by the modulated electric signal. Thus we express the modulation method as FM/IM (Frequency Modulation/Intensity Modulation) or PPM/IM (Pulse Position Modulation/Intensity Modulation) in optical telemetry.

To choose an appropriate modulation method, the characteristics of the biological signal, the multiplexing method and other practical factors have to be taken into account. In many of our applications, the PPM/IM and PIM/IM (Pulse Interval Modulation/Intensity Modulation) have been used. With pulse modulation, we can drive LED's

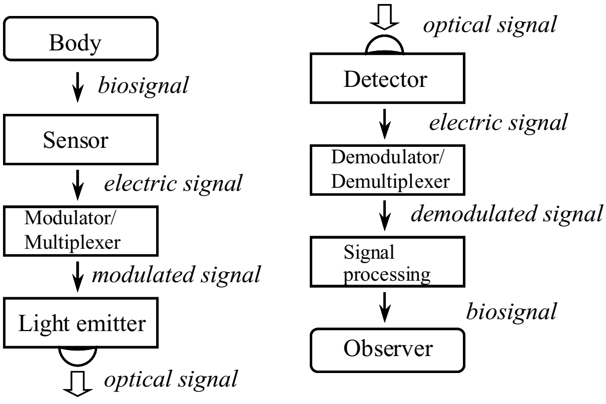


Figure 5. Signal flow in optical biotelemetry.

in higher luminance. With PPM and PIM, we can make the power consumption of the transmitter low by reducing the duty ratio of the light pulses.

3.3. Toward Intelligent Transmission

When we use light as a transmission medium, high-speed data communication becomes possible. The great advantage this brings is that we can use various techniques of intelligent communication. We can call this telemetry with intelligent communication, the telemetry of the next generation. It is compared with the conventional telemetry in which the measured biological signal is transmitted in the modulation signal of one-to-one correspondence.

As for the intelligent communication, the progress of the portable terminal which collects and displays a biological signal is remarkable. However, this article deals with the intelligent signal-transmission itself. There are two levels of intelligent communication, i.e. the level of a biological signal and that of a carrier signal. In the former case, the biological signal is processed using information processing techniques.

For example, the various redundancies such as noises and signal repetitions are eliminated in the transmission side.[6] In the receiving side, the necessary features of the biological signal are extracted from the transmitted signal. In the latter case, the communication part of the telemetry is made intelligent. It includes the error-control techniques in data transmission. Typical examples of the error-control techniques are the ARQ (automatic repeat request) and FEC (forward error correction). In both cases, we add some redundancy to the signal to transmit. Then, at the receiving side we detect the error caused in the transmission process, and take some measure for the detected error. With the ARQ, the system keeps requesting the repeated transmission of the data until no error is detected at the receiving side. With the FEC, the error is automatically corrected using the special code embedded (inscribed) in the transmitted signal.[5]

In such error-control processes, some duration of the data processing time is required. Generally, the longer time is required to use the more complicated error control to increase the reliability of data transmission. If this processing time exceeds the temporal capacity of the transmission system, the real-time operation is hindered. In biotelemetry, the real-time operation is often required. Therefore it is necessary to devise the error control method to secure high reliability while meeting the demand for the real-time operation. The balance between these contradicting requirements has been taken into account, for example by limiting the number of the repeated retransmissions in ARQ or by using a simple logic FEC such as a majority rule, etc.[7]

It should be noted that the difficulty of this problem has been gradually reducing due to the remarkable progress in the data-processing algorithm and the data-transmission speed.

3.4. Multiplexing Method

In optical biotelemetry, multi-channel data transmission is often required due to its large transmission capacity. To answer this, a multiplexing technique is necessary. The multiplexing techniques in optical communication are categorized largely into space-division multiplexing (SDM), wavelength-division multiplexing (WDM), time-division multiplexing (TDM), frequency-division multiplexing (FDM) and code-division multiplexing (CDM). Each has the following different characteristics and is chosen according to the purpose and the usage.

SDM uses the spatial difference in the light propagation path. It is effective for the telemetry using the direct-light transmission or the optical fiber transmission. With the indirect-light transmission, we have to separate the light-path by shading material, and the constraints in practical use are sometimes severe.

With WDM, we separate the channel by the difference of the wavelength of the transmission light. It can be realized relatively easily using light sources with different wavelengths and optical filters. It can be used in combination with other multiplexing techniques. Generally, it is difficult to have a large number of multiplexed channels due to the practical restrictions such as the monochromaticity of light source, the trade-off between the filter-bandwidth and the SN ratio of an optical signal, and so on. With the indirect light transmission, we cannot fully utilize the effective wavelength separability of the interference filter, since the orientation of light incidence to the optical detector is not constant.

With TDM, we allocate multiple channels on the time axis of the optical signal. With the recent rapid increase in the data transmission speed, the multiplexing of many channels has become possible. To perform efficient multiplexing in telemetry, the synchronization between multiple transmitters and receivers is necessary. For wireless synchronization, a two-way transmission is necessary and the receiving function is required for the apparatus equipped on a subject as well as the transmitting function. In biotelemetry, there is a fundamental demand to make the apparatus equipped on a subject as small as possible. Thus, the requirements of the synchronization often make it difficult to satisfy this demand.

With FDM, we differentiate multiple channels by the difference in the frequency of intensity modulation of carrier light. This can be done relatively easily. As mentioned above, a pulse modulation method is often used in optical biotelemetry. In the pulse modulation, the number of multiplexed channels is limited due to the higher harmonics of the pulse shape. With indirect-light transmission, the effect of multi-path transmission becomes non-negligible when the modulation frequency becomes large. Therefore, the bandwidth of signal transmission is limited.

With CDM, we encode the electric signal that modulates the light source, and differentiate multiple channels by the code. The spread spectrum is a typical example. This technique is suitable to the optical communication with which a broad band communication is possible. This technique has much useful potential such as strength against foreign noises and multi-path propagation. However, at present, some problems in practical use remain such as the complexity of the circuits both in a transmitter and a receiver.

4. PROPAGATION OF OPTICAL SIGNAL

For optical biotelemetry, it is necessary to understand the propagation of the optical signal in various conditions. This chapter summarizes the optical propagation in transcutaneous telemetry and ambulatory telemetry.

4.1. Optical Characteristics of Body Surface Tissue

In the transcutaneous signal transmission, the absorption and the scattering characteristics of body tissue are important. The optical absorption characteristics of biological tissue largely depend on the wavelength of light. Figure 6 shows the light attenuation in the tissues of body surface. This shows how the optical signal from the hypodermic (2 mm depth) light

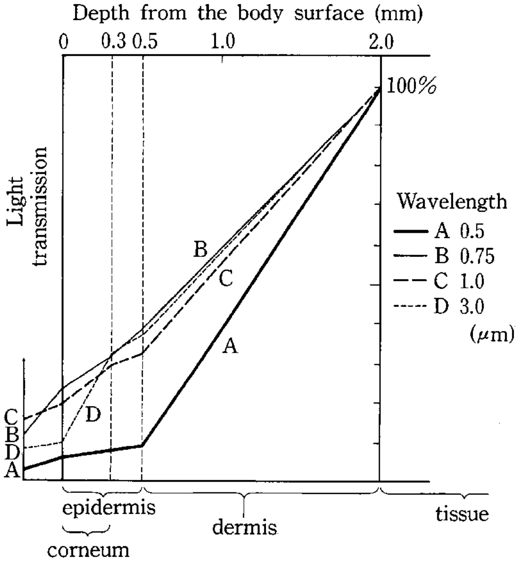


Figure 6. Attenuation of light in human surface tissue.

source is attenuated as the light propagates to the skin surface.[8] With near-infrared light, 10~20% light transmission is expected through the 2 mm skin tissue.

An example of the measured scattering characteristics of the skin is shown in Figure 7. This is the case of a mouse, and we can see the effect of relatively thick white fur.[8] Even with the complex emission-pattern of LED in the air, the angular pattern of light transmitted through the skin becomes fairly uniform in all directions. This is due to the strong scattering at the body surface tissue, and is also expected with human skin with less hair. This orientational uniformity of signal transmission is a significant merit in biotelemetry in which the subject moves around freely. Other optical properties of mammalian tissue can be found elsewhere.[9]

4.2. Distribution of Indirect Light in a Room

In a closed space like a room, ambulatory telemetry is possible using the indirect light scattered from the ceiling, the wall and the floor, etc. To understand the behavior of the indirectly scattered light, the spatial distribution of received light-intensity is investigated in a computer simulation.[10]

Figure 8(a) shows the conditions of the simulation. A light emitter with a hemispherical emission pattern toward the ceiling is placed 1.5 m high (a shoulder height of a human adult) above each of the floor mesh points. The light intensity received by the detector which is placed at the center of the ceiling is calculated according to the position of the emitter. The positions of the emitter are set at each of the floor mesh points. The light receiver is hung 0.6 m down from the center of the ceiling and the detecting face is oriented toward the ceiling or the floor. Figures 8(b)–(c) and 9(b)-(c) show the spatial distribution of the received light or the intensity of the transmitted signal.

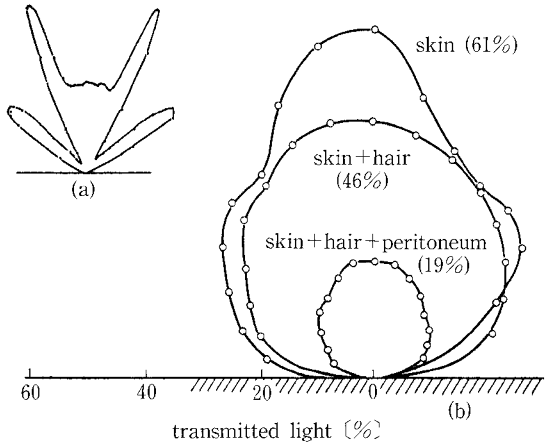
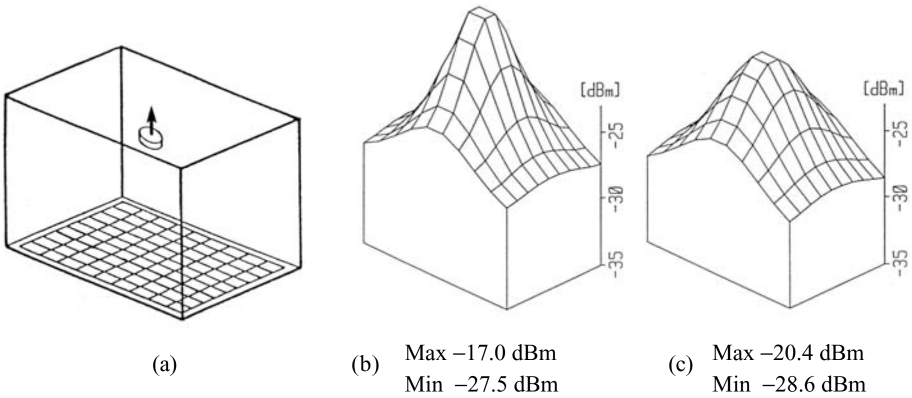


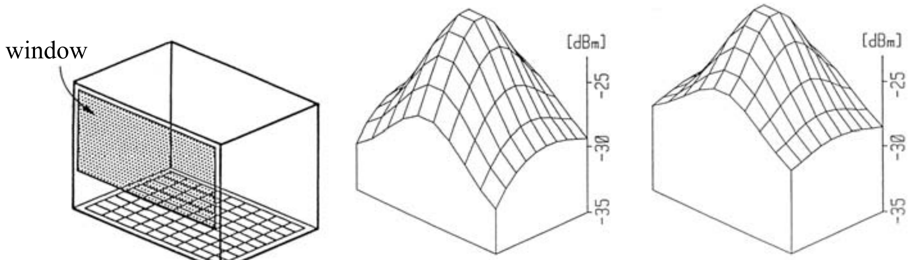
Figure 7. Scattering property of animal skin: (a) Radiation pattern of LED in air (wavelength 890 nm), (b) Radiation pattern of transmitted light through mouse skin (values are maximum transmission rates).

Figure 8(b) and 8(c) show the results with different orientations of the light detector. In both cases, sufficient amount of light for telemetry was received in all parts of the room even in a corner area due to the scattering effect. When the transmitter approaches to the central position of the floor, the received signal increases. In the case of Figure 8(c), the light-detecting face of the receiver is pointed up towards the ceiling and the variation of the received signal becomes relatively small. In ambulatory telemetry, the small variation is often more preferable than the high peak-intensity of the received signal. That is, we can



(a) (b) Max −17.0 dBm Min −27.5 dBm (c) Max −20.4 dBm Min −28.6 dBm

Figure 8. Conditions and results of simulation of indirect scattered light: (a) dimension of room 6.4 m width, 4.2 m length, 2.7 m height; reflection coefficient of inner surface of room 0.7 (Lambertian surface), optical power of transmitter 1 W; receiving area of receiver 10 × 10 mm^2; directivities of transmitter and receiver are both cosine. (b) intensity distribution of signal transmission with receiver facing down toward floor, (c) intensity distribution of signal transmission with receiver (hung 0.6 m down from ceiling) facing up toward ceiling.



(a)

(b) Max –20.6 dBm
Min –31.5 dBm

(c) Max –20.4 dBm
Min –28.6 dBm

Figure 9. Change of signal transmission caused by window: (a) position of window, (b) with window, (c) without window.

expect stable telemetry with the light detector hung down from the ceiling with its receiving face pointed up towards the ceiling.

In the telemetry using indirect light transmission, the room is filled up with the signal light by the scattering from the ceilings and the walls. This is the basic principle of ambulatory telemetry. Thus, the signal strength is reduced considerably when there is an open-window or a dark curtain on the wall. To examine this effect, a simulation was conducted for the case when there is a large open-window (the wall with 0 reflection coefficient) covering most of one of the walls. Figure 9 shows the result. The signal strength decreases when the transmitter approaches the window. However, the decrease is small (2-3 dB) and there is little problem in practice. This example typically shows that the distribution of the indirectly scattered light is relatively stable against the change in environmental physical conditions.

The validity of this result of simulation was confirmed in the real measurement, as well.[10] An example of the measured result is shown in Figure 10. This is the spatial

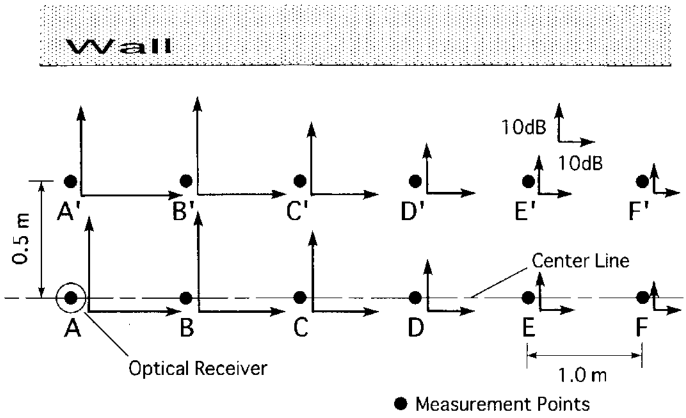


Figure 10. Measured distribution of signal transmission in corridor: length and orientation of vectors indicate CN ratio of received signal and direction of subject's face, respectively.

distribution of the received signal in the corridor in which two sides are considered as open space. (W2.1m × H2.7m × L30.0m) This shows the signal strength received at the ceiling at the position indicated in the figure. The subject equipped with a light emitter (1W optical power) on both shoulders stands at different points (A-F, A'-F') facing against a wall or facing along the center line of the corridor. The vectors in the figure indicate the orientation of the subject and the magnitude of the received optical signal in C/N (ratio between the strengths of carrier and noise). This result shows that we can expect more than 10 dB C/N in entire area by installing light detectors every 8–10m. Through these analyses it was confirmed that we can realize the ambulatory biotelemetry using indirect light transmission in a regular room with little effect from the subject's position and movement.

4.3. Optical Signal Propagation in Open Space

In the ambulatory measurement using indirect light transmission, the optical signal filled the closed space, generally. Therefore, it is considered to be effective in a patient's room, an examination room and a cabin of a vehicle, but not in an open space such as outdoors. Two techniques can be used to overcome this problem.

One is the use of direct light transmission with a tracking function. Using a beam of light, data can be transmitted by tracking either the transmitting side or the receiving side. Various systems that track a light spot automatically have been commercialized, and it is not difficult to follow the speed of a human movement. However, when we use direct light transmission, we always have to secure the light propagation path.

In another technique, we use the indirect light transmission available in an open space. For instance, the ambulatory measurement becomes possible to some extent using ground reflection effectively or using many receivers equipped with a diffuser or a reflector. An example of the unit of reflectors and a photo-detector is shown in Figure 11. 8–16 units of this structure are combined around the z-axis in the positions of rotational symmetry. With

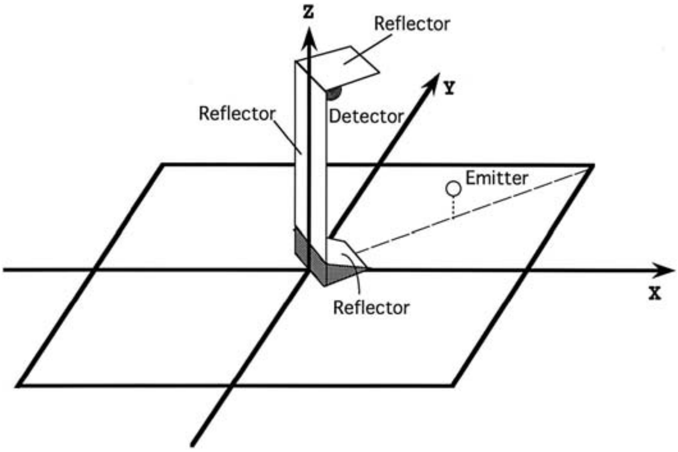


Figure 11. An example of reflector structure for indirect light transmission in open space.

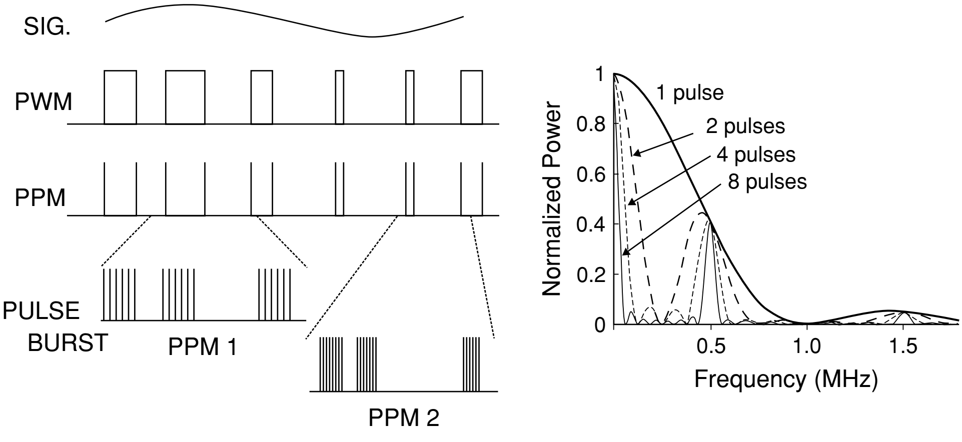
this kind of receiver, we can achieve ambulatory measurement with a light emitter of 1W optical power within 10m distance from the receiving unit in an open space.

5. MULTIPLEXING IN OPTICAL TELEMETRY

As mentioned in Sec.3.4, there are various multiplexing techniques for optical telemetry. Every technique has problems to be solved in the practical use for optical telemetry. We have also developed the multiplexing technique suitable for the biotelemetry using indirect light transmission.[11] Here, we introduce two representative techniques.

5.1. Pulse Burst Method

In the optical data transmission in free-space, the pulse modulation technique is more advantageous than the CW modulation technique from the view points of optical transmission power and noise immunity. The pulse width modulation (PWM) is a typical method of the pulse modulation technique. We can use the PWM in a relatively simple manner, and the demodulation is easy, as well. However, the power consumption of PWM is generally high. So, we can modify the PWM as the pulse position modulation (PPM) by representing the positions of the rise and the fall of the PWM pulse by two short pulses. The first and the second pulses indicate the temporal positions of synchronization and modulation, respectively. In the proposed pulse-burst method, we make the above mentioned short pulse into a train of narrow pulses. This train of pulses consists of a few pulses to several tens of pulses. In multiplexing, each channel is distinguished by the frequency of the burst pulses. Figure 12(a) shows the principle of this technique, and Figure 12(b) shows the frequency spectra of the pulse burst signal with 500 kHz repetition of 1 μsec width pulses. As the number of the pulses increases, the spectral peak becomes narrow. In this case, we can expect several channels multiplexing with 8 pulses in a single burst. In experiments, the



(a) (b)

Figure 12. Pulse-burst multiplexing technique: (a) principle, (b) power spectra.

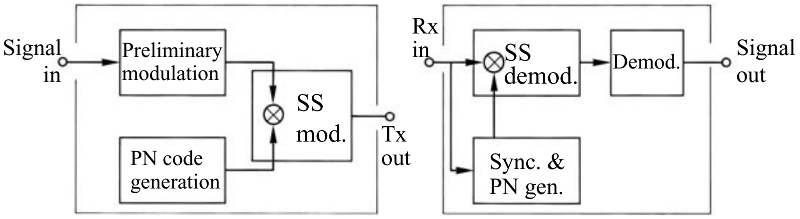


Figure 13. Telemetry system using spread spectrum technique.

effectiveness of this pulse-burst technique in the multiplexing of several channels has been confirmed.[11]

5.2. Spread Spectrum Method

For biotelemetry using indirect light transmission, we have proposed the application of the spread spectrum (abbreviated as SS) method as a promising multiplexing technique. With the SS method we modulate the signal to be transmitted into a much wider bandwidth than that required for the original signal.

Figure 13 shows the principle of the SS modulation system we have developed for the optical biotelemetry. In this system, we modulate the signal to be transmitted into a digital signal as the first modulation. Then, as the second modulation, we modulate the digital signal by multiplying it with a pseudo-noise signal generated in the transmitter. Since the pseudo-noise signal has much wider bandwidth than the original signal, the spectrum of the modulated signal is spread widely. In the receiving side, we take the correlation between the received signal and the same pseudo-noise signal as the transmitting side. As a result, we can obtain the digital signal of the first modulation. By demodulating the digital signal, we can recover the original signal. Through these processes, the effects of noises, interferences and multi-path propagation are greatly suppressed. With this SS method, we can multiplex more than several tens of channels relatively easily by using different kinds of the pseudo-noise. On the other hand, a wide-band transmission is required to utilize this technique effectively. Since the wide width of the transmission band is one of the typical merits of optical biotelemetry, it is suitable to the SS method. The detail of this technique and the results of experiments can be found in the reference[12].

6. APPLICATIONS OF OPTICAL TELEMETRY

We have applied the methods and techniques previously mentioned to realize the optical biotelemetry. Let us see some of them as concrete examples of optical biotelemetry.

6.1. Transcutaneous Biotelemetry

One of the techniques to take the internal information out of the body is the transcutaneous biotelemetry. The radio-capsule is one of the well-known examples. With this technique, we encapsulate pH electrodes or a temperature sensor in a swallowable small

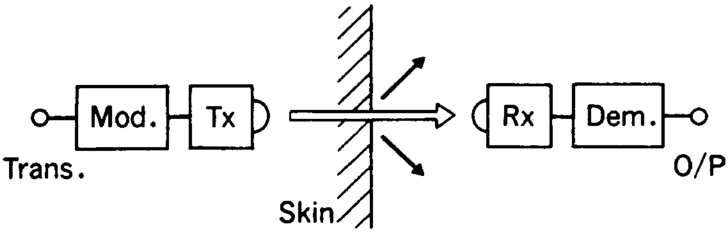


Figure 14. Principle of transcutaneous optical telemetry: Trans: transducer, Mod: modulator, Tx: transmitter, Rx: receiver, Dem: demodulator, O/P: output.

capsule. It transmits the pH or temperature information of the digestive tract from the inside to the outside of the body by a radio wave. We can apply the principle of optical telemetry to this purpose, also.

We place a light emitting element inside the body and receive the light propagated through the body tissue. Figure 14 shows this principle. We have confirmed the feasibility of this principle through various fundamental studies.[8] Then, a telemetry system was test-manufactured, and it was applied to an animal experiment.[8] Figure 15 illustrates the animal experiment. The electrodes, the transmitter and the light emitters were implanted inside the body of a rat. The light signal diffusely propagated through the skin was captured by the optical receiver placed outside the animal cage. In this way, the internal ECG can be measured remotely without restraining the animal. There is no need to attach any element on the body surface of the animal. This makes the animal experiment much easier than using many attachments on the body.

The size of the implanted transmitter was 40 × 25 × 15 mm^3 and the weight was 16.6 g. The transmitter operates for about 100 hours in continuous use. We installed a power switch which can be driven by the illumination of near-infrared light pulses from outside the body. Therefore, the battery life was extended considerably by turning on the power only when it was necessary. The light emitters were two LED's with the optical power of 70 mW in total. The transmission range was 3 m in a free space. If there is a scattering object such as a wall or a human body within about 1 m, the telemetry was possible even when the direct propagation path was intercepted.

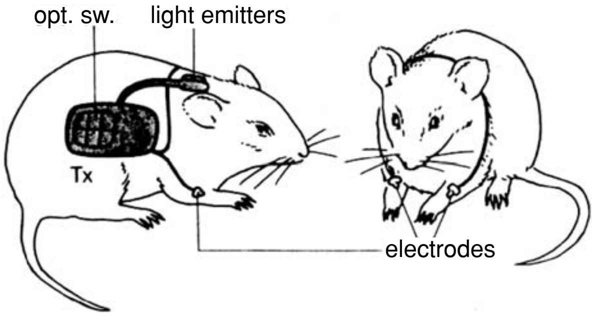


Figure 15. Animal experiment of transcutaneous optical telemetry: opt. sw.: optical switch.

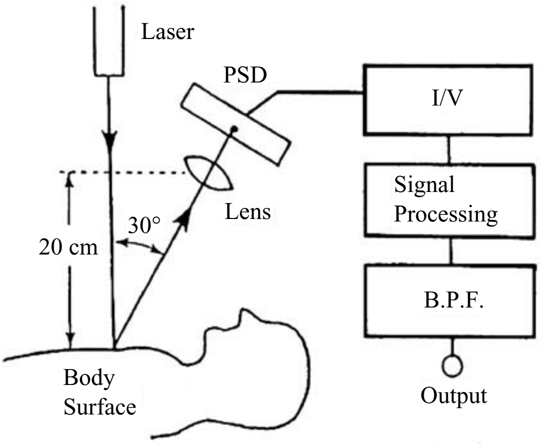


Figure 16. Principle of surface displacement measurement by light.

6.2. Non-contact Measurement of Body Surface Displacement

We can measure the displacement of the body surface without any direct contact by using light. Figure 16 illustrates the principle of this technique. This example shows that we can use light not only for the signal carrier but also for the sensor to obtain a biological signal.[13] When we illuminate the measurement point on the body surface with a thin parallel beam of light, a scattering light spot appears on the body surface. With a lens, the scattered light is focused on a solid-state position sensitive device (PSD) as a light spot. Since the body surface displacement in the direction of the light beam changes the position of the light spot on the PSD, we can measure the displacement as the current change of the PSD. We used a laser diode (1mW, 780 nm) as a light source, and a one-dimensional PSD (1 × 12 mm^2 effective receiving area) as a light receiver. The sensitivity and the accuracy were 200 mV/mm and 0.01 mm (frequency bandwidth 0.1–20 Hz), respectively.

This principle was applied to the respiratory and cardiac monitoring of neonates.[13] Figure 17 shows the concept of this technique. Figure 18 shows the result of the measurement

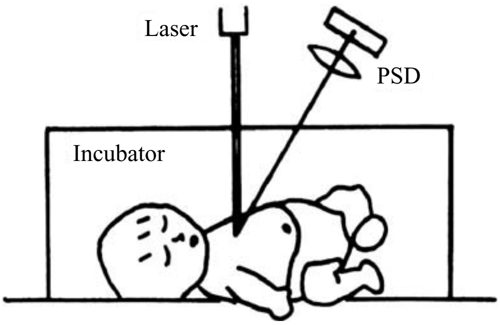


Figure 17. Respiration monitoring of neonate by light.

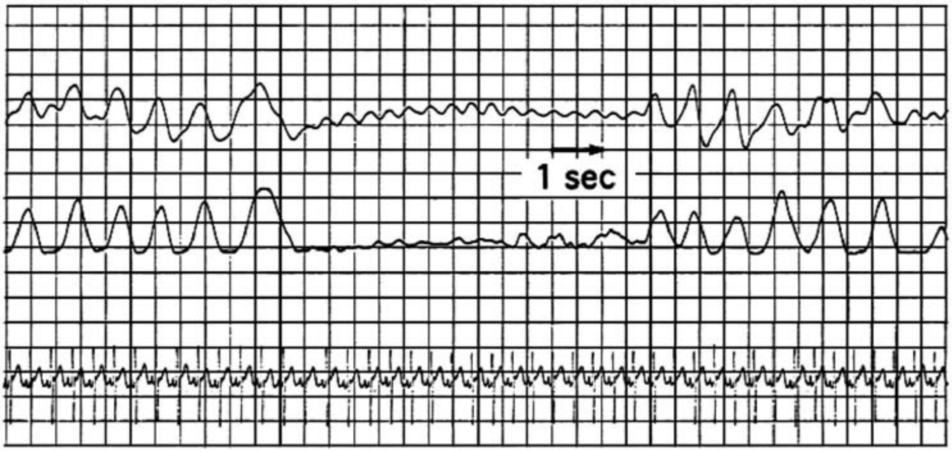


Figure 18. Measured results of chest movement of neonate: (a) optical technique, (b) impedance measurement, (c) ECG.

obtained with the neonate lying on the back. It shows the waveform obtained by the proposed technique (Figure 18(a), 0.1–3 Hz bandwidth), the respiration waveform obtained by an impedance measurement technique (Figure 18(b)) and the ECG (Figure 18(c)) for comparison. Figs.18(a) and 18(b) show the temporary apnea between normal respirations. Even with a simple band-pass filtering, the waveform obtained by the optical technique shows a good agreement with that obtained in the conventional impedance measurement. In Figure 18(a) we can observe the fluctuation in the apnea period. In comparison with Figure 18(c), it was found to be the cardiac movement of the chest wall. This shows that we can monitor the vital sign of neonate with a beam of light and without any electrodes and cables.[13]

There have been different applications of this technique, or the optical non-contact measurement of body surface movement. They include the measurements of a mechanocardiogram and the pulse propagation velocity.[14] It has been shown that this technique is also useful in detecting the blood vessel constriction due to physical and mental stress without any physical contact on the body.[14]

6.3. Ambulatory Telemetry

One of the most important purposes of biotelemetry is to measure physiological signals without any constraint on the natural activity of the subject. The ECG telemeter which has been used in clinical routines is a typical example. In hospitals and medical institutions, various kinds of telemeters have been used, such as integrated monitoring in ICU and CCU, and daily cardiac monitoring of hospitalized patients. In almost all the cases, a radio wave has been used as the transmission medium in these kinds of telemetry. Recently, EMI problems have become more serious than ever due to the deterioration of the electromagnetic environment in hospitals and the enforcement of legal restrictions.

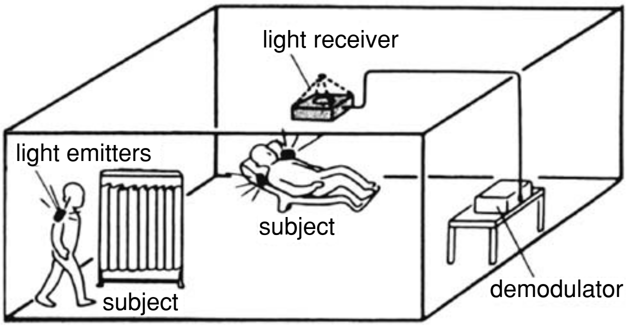


Figure 19. Principle of ambulatory telemetry using indirect light transmission.

Many of these problems can be solved by using light as a transmission medium for the biological information. If we use indirect light which has been reflected and scattered at a ceiling, a floor and walls, we can transmit a stable signal by light without the problem of interception of a direct path. Figure 19 shows the principle of this technique. The biological or physiological signals obtained from a subject are modulated for transmission. If multi-channel data transmission is required, they are multiplexed into a single channel of data. The modulated signal is converted into a light signal at a transmitter. The light signal is emitted, reflected and scattered at the inner surface of a room, and eventually fills the room. In this way, we can maintain the signal transmission by the indirect light transmission even if the direct light path between the transmitter and the receiver is intercepted.

Figure 20 shows the outline of the system to realize this technique. This system consists of a transmitter to collect and to transmit biological signals and a receiver to receive and to display/record the signals. To examine the effectiveness of this technique, an optical telemetry system was manufactured. Table 1 shows major characteristics of the system. The effectiveness and the usefulness of this technique have been confirmed in the measurement

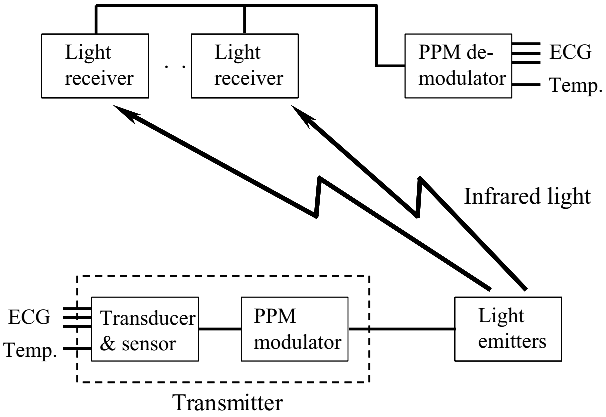


Figure 20. Telemetry system using indirect light transmission.

Table 1. Performance of Optical Biotelemetry System

TRANSMITTER		LIGHT EMITTERS (a set of two)	
ECG	3 ch. standard limb leads or precordial unipolar leads	Light emitter	80 IRLED's (940 nm)
signal bandwidth	0.05–100 Hz	Total optical output (when pulse on)	1 W
non-linearity	less than 4%	Current drain	20 mA
total gain	46dB	Dimension	L90 × W80 × H18 mm^3
Temperature	1 ch. thermistor	Weight	85 g
temperature range	0–42 deg. C		
time constant	0.42 deg/s		
Modulation	4 ch. PWM/PPM/IM		
Pulse frequency	2.6 kHz	LIGHT RECEIVER	
Pulse interval	ECG ch. 0.3 ms	Photo detector	PIN Si photo diode (effective receiving area 100 mm^2)
	Temp. ch. 0.6 ms		
Pulse width	2μs	Optical filter	long pass filter (cut off wave length 800 nm)
Current drain	1.5 mA		
Dimension	L36 × W60 × H138 mm^3	Dimension	L100 × W120 × H50 mm^3
Weight	350 g	Weight	450 g

with a subject in various moving conditions. The optical telemetry system using indirect light transmission developed in this study has been used for the biological data acquisition of a payload specialist of a space shuttle in the space-lab.[15]

6.4. Multi-channel Biotelemetry

Using the biotelemetry technique, we can transmit biological signals and medical data to a remote place. The ECG transmission from isolated islands and remote rural areas using a public telephone network is a well-known example. With the optical technique, we can realize the large-capacity high-speed data transmission.

Figure 21 shows the principle. Different kinds of biological signals and medical data are multiplexed in a primary station. They are transmitted through an optical communication channel. The optical signal is received at the secondary station and demultiplexed

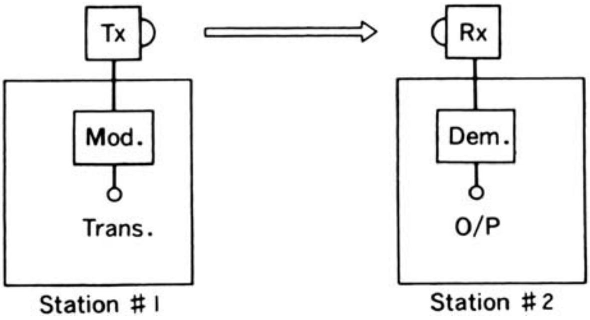


Figure 21. Principle of multi-channel data transmission to remote place by optical telemetry: Trans: transducer, Mod: modulator, Tx: transmitter, Rx: receiver, Dem: demodulator, O/P: output.

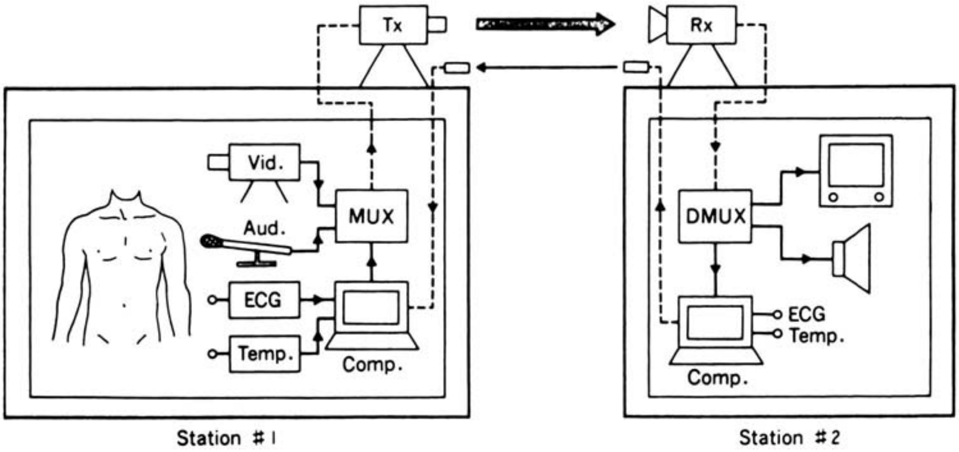


Figure 22. Developed system for multi-channel data transmission to remote place by optical telemetry:
Vid: video signal, Aud: audio signal, MUX: multiplexer, Tx: transmitter, Rx: receiver, DMUX: demultiplexer, Comp: computer, broken line: optical fiber.

to reproduce the original signals and data. This technique not only enables us to separate the data collection site and the data analyzing site, but also enables us to transmit many different kinds of data to a remote place simultaneously in real time. In this way, we can significantly increase the mobility and the flexibility of each station. This is particularly important in the case of animal or human experiments and clinical practices. In these cases, it is generally difficult to bring large data collection/processing equipments into the measurement site. Since we can send multi-channel data including color moving images and audio signals in real time, this technique provides a powerful tool for telemedicine and home-care medicine.

Figure 22 illustrates the outline of the system test-manufactured to show the possibility of this technique. From the primary station to the secondary station, the biological signals (color video image, audio signal, ECG, EEG and body temperature) are modulated by the PPM/IM method and transmitted through open air. In the return-path, the signal for ARQ is transmitted back from the secondary station to the primary station. Since the capacity of the information through this return-path is very small such as the existence of channel disconnection and the state of receivability, four kinds of signals were enough. They were differentiated by the frequency in an FM/IM modulation.

An experimental system was developed and the effectiveness of this technique was examined.[16,17] In the experiment, a color moving image, an audio signal and three channels of biological signals (ECG, EEG, body temperature) were transmitted simultaneously to show the condition of a patient. In this experiment, the signals were transmitted by light through open air. The transmission distance up to 1 km was confirmed with our system. Using a laser with higher optical power, larger transmission distance is expected. If the mobility of the primary station is not required, we can use an optical fiber communication. Then, the transmission distance can be much larger than the open-air communication.

6.5. Data Transmission between Medical Equipments

With the recent increase of various electrical equipments in medical institutions, there has been a strong demand for them to be integrated into a small number of systems. Particularly in an operating room and an ICU, the centralized control and data processing are required among many monitoring, imaging, and automatically controlled equipments. However, such integration inevitably increases the number of electric wires connecting the equipments. This not only hinders the operation but also increases the risk of accidents such as the leakage of electric current. The wireless transmission of data and control signals is one of the solutions. However, the use of a radio wave in a hospital is not preferable due to the problem of electromagnetic interference. We have applied the optical biotelemetry technique to answer this demand.

For multiplexing we have used the SS method which is robust against various noises and can provide many channels for multiplexing. To examine the feasibility of this technique, we have developed a central part of the transmission system.[12] Figure 23 shows the outline of this system. The digital data to be sent is fed from computer A through an RS-232C interface. In the transmitter, the data is processed in the preliminary modulation circuit to be suitable for the next SS modulation. Then, it is multiplied with the pseudo-noise (PN) code generated in the transmitter. For the preliminary modulation and the PN code, we used the ASK (Amplitude Shift Keying) and the Gold series with 127 chips period. To make the data transmission rate at 9600 bps, the clock frequency of a chip was set at 7.315 MHz. The SS modulated signal is emitted from the LED array which consists of 60 LED's (nominal optical power 30 mW each, wavelength 850 nm). The indirect light scattered by a ceiling, a floor and walls reaches the Si-PIN photodiode and is transformed into an electric signal. The received signal is amplified and its frequency is shifted to 215 MHz in an up-conversion circuit using a double balanced mixer (DBM). This is the operating frequency of a surface acoustic wave (SAW) convolver. In the receiver, the time-reversed Gold series which is the same as that used in the transmitter is generated. This PN code is also frequency-shifted to 215 MHz and fed to the SAW device. In the SAW device, the received signal is convolved with the PN code, and the correlation data is obtained in real time. After this SS demodulation, the signal is demodulated according to the preliminary modulation. In the developed system, the signal is processed in the envelope detection

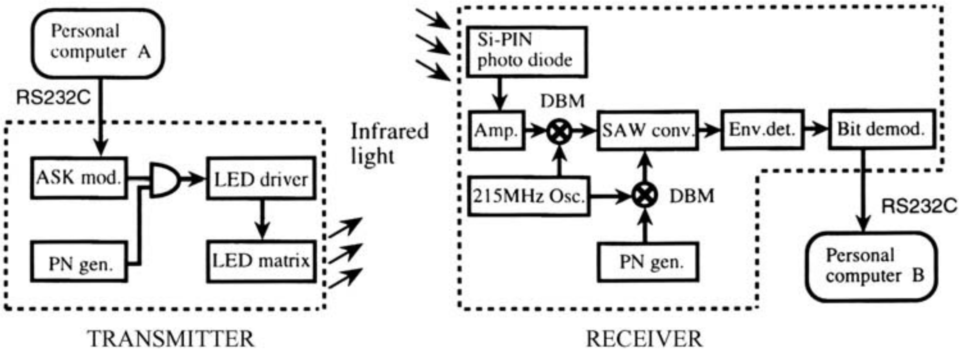


Figure 23. System for optical data transmission between medical equipments using SS technique.

and the bit demodulation circuits. The bit-data is fed to computer B through an RS-232C interface and an original signal is reproduced in the computer.

We have manufactured an experimental system which consists of two transmitters and one receiver. In the analysis of transmission characteristics, the practical feasibility of the proposed technique has been verified.[18,19]

7. CONCLUSIONS

A concept of optical biotelemetry has been proposed and summarized. Conventionally, a radio wave is commonly used for biotelemetry. However, optical biotelemetry is possible in various applications as shown in this chapter. Due to the recent progress in optical and electronic technologies, the introduction of the optical technique can realize new useful features. We do not intend to replace radio telemetry by optical biotelemetry. They should be used to support each other. For example, in a closed space such as in a building, optical telemetry has many useful merits. However, in open space such as outdoors, radio telemetry has much greater transmission range.

Until very recently, the applications of biotelemetry have been limited in a relatively small area, such as ECG telemetry and animal tracking. However, the demand for biotelemetry has been steadily expanding. There has been a notable change in our society. Cardiac and cerebral disorders are increasing rapidly as the elderly population increases. The necessity of homecare and telemedicine is higher than ever. The importance of rehabilitation medicine and sports medicine has been widely recognized. Health management and self-diagnosis have become common among the general public. The demand for providing emergency medical support to moving vehicles such as ships, aircrafts and space ships has been increasing, as well.[20] In these social trends, biotelemetry has been expected to play an important role as a key-technology. Optical biotelemetry is only one of the techniques of such biotelemetry. But it has promising potential to open a new possibility to answer the above demands.

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