Current Status of Infrared Technology

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Infrared science and technology has been contributing to the four important national priority researches which are nano-, bio-, information- and environmental technologies. In this manuscript we discuss the current status of the infrared science and technology as well as its crucial role in the four technologies.

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1. Introduction

The 21st century is called “Epoch of Light”. The radiation of infrared exists in an interesting frequency region where various kinds of researches merge from both sides of visible light and radio frequency in the electromagnetic waves. The infrared science and technology (IrST) have been utilized in a wide range from a frontier science to public welfare, and then they are expected in the 21st century to progress and expand more and more throughout the world.

A several years ago, the Japanese government has determined the following technologies as important national subjects of research; (1) nano- (2) bio-, (3) information- and (4) environmental -technologies. The IrST are also closely related with these subjects. It is, therefore, important to clarify the relations among them in order to progress and distribute the IrST. Hence the Investing R&D Committee on Multiple Infrared Application Technology was established at the Institute of Electrical Engineers of Japan in 2002 on a three-year scheme in order to give a direction of infrared research looking over the contributions of the IrST to four technologies mentioned above as well as others. The committee has published a report “Infrared Technology for Four National Priority Researches” on June, 2006.

Although infrared radiation seems apparently to be independent of nano-technology because of the inherent long wavelength, it is strongly related on such the nano-technology as seen, for example, in a device using quantum-well. An infrared sensor arrayed with high density is produced by nano-technology and it is utilized as an infrared imager for various kinds of applications, e.g., security,

environmental measurement, etc. In bio-technology, far-infrared radiation is applied for surgical method. On the other hand, near infrared radiation is applied to the tomographic image of biomedical tissue. In the information-technology, infrared radiation is applied to not only short haul- but also long distance-communication such as satellite communications in the space. The IrST such as spectroscopy, measurement and sensor technology are applied more widely in the environmental technology than in the other research subjects.

Far-infrared among the IrST is recently paid attention as terahertz (THz) radiation. The terahertz technology has been rapidly progressing which depends on the whole development of sources, oscillators, lasers, detectors, mixers, spectrometers and so on. Terahertz time domain spectroscopy is positioned on an extension line of excellent results of these researches.

This special issue intends to publish the up-to-date researches on the IrST especially with respect to the important national priority researches mentioned previously including researches such as sensor, radiator, optical element, etc. The current status of the IrST in their respective fields is briefly described in the following sections.

2. Nanotechnology and Materials

The development of materials has played a crucial role in the infrared technology. Recently, in addition to the development of materials themselves, fabrication techniques of materials (nanotechnology) increase their importance because they create new functions. The relationship between the nanotechnology and various fields of infrared technology is shown in Fig. 1. Here, we briefly review the nanotechnology and materials for use in infrared science and technology.

2.1 Sources Semiconductor lasers represented by the double hetero (DH) lasers obtain their high efficiency by confining electrons and light in one dimension. In the semiconductor structures having layer thickness less than 10 nm, the electronic levels become discrete and the characteristics of the laser oscillation are improved by the quantum effect. Although the electrons can move freely in the

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Fig. 1. Relation between nanotechnology and infrared technology

direction parallel to the layer for the case of the quantum well, the electrons are confined three-dimensionally and the energy levels become discrete in the quantum dots. The quantum dot lasers aim at highly stable laser oscillation by using these discrete energy levels. This idea was proposed by Arakawa and Sakaki in 1982⁽¹⁾. However, the fabrication technique was immature at that time and the three dimensional confinement was realized by applying magnetic fields. The improvement of the threshold current, modulation characteristics, and spectral features was demonstrated for the laser action. The research of the quantum dot lasers has progressed recently by the development of the fabrication technique of nanostructures. The room temperature oscillation has been realized with the InAs dots on the GaAs substrate and the low threshold current and stable temperature characteristics were demonstrated⁽²⁾. A single photon source has also been made by using an InAs/InP quantum dot⁽³⁾.

In 1994, a new type laser utilizing the sublevel transition in semiconductor quantum wells has been demonstrated⁽⁴⁾. The light amplification occurs through the cascading transitions of injected electrons between neighboring discrete levels. This new type laser has been called a quantum cascade laser and the oscillation in the terahertz region was realized recently⁽⁵⁾.

2.2 Detectors As well as sources, the new detectors utilizing nanofabrication have appeared. As a material for the infrared region, $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ (MCT) is well known. However, it is difficult to make materials appropriate for use in the wavelength region longer than 10 μm . In order to make detectors working in this region, detectors utilizing the subband transition of quantum well structures (quantum-well infrared photodetector, QWIP) have been developed⁽⁶⁾. However, the simple QWIP is not active for the normal incident light because the transition moment is perpendicular to the layer. In order to overcome this deficiency, surface grating structures and random scattering layers were introduced. In contrast to the quantum well structure, the quantum dot does not have a selection rule like quantum wells and the quantum dot can detect light incident normally on the surface with the dots. Infrared detectors utilizing the self-grown dot of InAs have been developed⁽⁷⁾. The far infrared single photon detector was developed by using the quantum dot in which the electrons are confined by the micro electrodes⁽⁸⁾.

One of the recent topics of high-temperature superconductor is intrinsic Josephson effect. Yamashita and coworkers have observed clear Shapiro steps for Bi high-temperature superconductors by using new microfabrication technique⁽⁹⁾. This experimental result demonstrates the possibility of developing

new highly sensitive mixers using the intrinsic Josephson effect in near future. As to the conventional metal superconductors, the superconducting tunnel junction (STJ)⁽¹⁰⁾ and superconducting transition edge (TES)⁽¹¹⁾ sensors have made a great progress as detectors which can measure the photon energy owing to the development of the fabrication technique and near infrared detection has become possible. By the combination of microbridge and antenna, millimeter waves can be detected with bolometric or nonbolometric effect.

2.3 Photonic Crystals Photonic crystals are artificial materials having structures with a period comparable to the wavelength⁽¹²⁾. The photonic band gaps are formed like electronic bands in crystals⁽¹³⁾. In early days, the demonstration of the photonic band gap formation has been demonstrated in the microwave region. With the development of the semiconductor microfabrication technique, the photonic crystals in the telecommunication wavelength region (1.5 μm) have been made and now are expected to be used for components of optical telecommunications. It is possible to lowering the threshold current by using the photonic band gap and novel optical properties like superprism and superlens effects have been demonstrated.

2.4 Near-field Microscope The spatial resolution of the conventional optical microscope is determined by the wavelength of light. To overcome this limit, near-field optical microscope has been proposed and demonstrated. The near-field microscope has been made in the millimeter wave region by using the slit-type probe and the spatial resolution of 83 μm has been attained at the wavelength of 5 mm⁽¹⁴⁾. Usually the sensitivity is limited by the hole diameter of the probe. However, Keilmann and coworkers have demonstrated that this limitation can be overcome by just placing a metal wire at the hole making the structure like that of the coaxial cable⁽¹⁵⁾. Further, they reported that the increase of the signal intensity and the spatial resolution less than 10 nm can be obtained by utilizing the Frölich resonance of the phonon at 1000 cm^{-1} of SiC⁽¹⁶⁾.

3. Life science and Technology

Life science was originally considered as study of life containing genes etc. itself. From the larger viewpoint, it is thought to be useful in order to maintain human beings' life. The infrared light and the infrared technology have played the important role in the life science.

Radiant heating by infrared rays is applied to medical care as thermotherapy. The history of a thermotherapy is old and medical treatment using laser is put in practical use in dentistry, dermatology, ophthalmology, etc. in recent years.

It has been reported that the oxygen concentration information in the head of a cat was obtained by using the near infrared light which was capable to penetrate the biological tissue in 1977⁽¹⁷⁾. After this report, the optical measurement and the infrared spectroscopy for the living body has been investigated, especially the image technology using near infrared light was remarkably developed. The role of the infrared light in medical field falls into two categories of the therapy and the diagnosis.

The optical measurement is non-invasive and is capable to distinguish biological material using spectrum information. The biological tissue has the weak absorption region in the wavelength region from 0.7 to 1.1 μm in the near infrared, and it is used for biomedical measurement well. The pulse oximeter, the near

infrared oxygen monitor and OCT (optical coherence tomography) have been already used for medical diagnosis.

OCT is an imaging technology using interference of low coherent light. The MIT research group reported the scanning OCT which was capable to construct the cross-section image in order to apply the funduscopy examination in 1991. Investigations on improvement of spatial resolution and fast scanning for image have been made intensively⁽¹⁸⁾.

The functional near-infrared spectroscopy⁽¹⁹⁾ and the optical topography, which were multi-channel near-infrared oxygen sensors, were developed for measurement of cerebral nerve activity.

In recent years, the molecular imaging which aims to measure and display the biological process in living cells is attracting attention⁽²⁰⁾. Imaging of molecular dynamics in living cells has been performed by use of by the fluorescence protein. Moreover, the fluorescence tomography has been investigated on the basis of technologies of the conventional optical tomography and the diffuse optical tomography for application of small animals.

4. Infrared Wireless Communication

4.1 Feature of Infrared Wireless Communication This section describes the so-called optical wireless communication technology which uses infrared rays as a carrier through free space. The infrared wavelength mainly used now is 0.7 μ m to 0.9 μ m band in which a light emitting diode (LED) or a laser diode (LD) of GaAs-based semiconductors and a photodiode (PD) of Si can be utilized at a low cost to the communication systems as a emitter and as a receiver respectively. Moreover, the infrared wireless communication system of 1.3 μ m and 1.5 μ m bands, in which development of semiconductor devices of the optical fiber communication are progressing, are also carried forward for aiming at an application to high-speed communication⁽²¹⁾. In this article, a term called “infrared” wireless communication is used instead of “optical”.

In the wireless communications through free space, a carrier wave is influenced by the atmosphere, which is originated by absorption and scattering due to molecules and dusts and scintillation due to turbulence of the atmosphere. Some strong absorption bands by water vapor and carbon dioxide exist in an infrared region and the communication more than short distance communication is difficult there. The scattering is mainly caused by the dust floating in the atmosphere, and there is less influence in longer wavelength of the infrared. The scintillation also has less influence in longer wavelength at a dependence of $\lambda^{-7/6}$ on the wavelength λ .

Moreover, the weather as rain and fog, and also by the disturbance light as sunlight and lighting also affect the outdoor wireless communication. The influence of the weather does not become a problem in indoor wireless communication, but in contrast it becomes an important problem in communication on out-of-doors. Rain and fog produce the large transmission loss mainly by scattering in the whole wavelength region including visible light and infrared. The influence of sunlight or lighting occurs by direct light and scattering light and has also less influence for longer wavelengths. The thermal radiation of the atmosphere and an object becomes a problem from the wavelength longer than 3 μ m as a background light.

Although the wireless communications using radio wave of frequencies from several 10 MHz to several 10 GHz has spread

Table 1. Advantages in characteristics of infrared and radio wave

Infrared	Radio wave
Small and lightweight	Strong against snow and fog
Broad band	Comparatively strong against rain
License-free	Robust to shields
Robust against EM-noise	(Transmission by diffraction)
Physical secrecy (Shield is easy)	Safe to eyes

through the society widely by a cellular phone, a wireless LAN and a fixed wireless access, the infrared wireless systems have superiority in such applications as high-speed communications, physically secure communications and license-free and easily linked communications by utilizing its advantageous characteristics. Each advantages of the infrared light and the radio wave is shown in Table 1. Moreover, the infrared wireless communication supplies niche and complementary applications taking advantage of needlessness of cable construction and a short time until start of operation as a distinction from the optical fiber and electric cable communications which support the present-day Internet and telephone networks.

A form of infrared wireless communication can be divided into two kinds from a spread of a transmission beam, which are large beam and narrow beam communication systems. From a viewpoint of usage, the large beam system offers mobile and personal communications and indoor links with low electric power using a small antenna and simple devices, and the narrow beam system does a fixed and long distance outdoor links and a space-division multiplexing communication using a big antenna. The large beam communication is performed through a scatterer or a reflector besides through a straight path, and in contrast the narrow beam communication mostly consists of only a straight path link within view⁽²²⁾.

4.2 Short-range Infrared Wireless Communication The IrDA (Infrared Data Association) were founded in 1994, and it made the standardization on wireless communications with infrared technology in short distances (1 m for regular use and 0.2 m for power-saving use) such as between PCs and peripheral equipments. The infrared transmission system of the access speed of 115.3 kbps to 16 Mbps was defined as an IrDA standard then. Infrared transmission devices up to 4 Mbps have so far mounted for the present note PCs.

Now, the infrared transmission component of the IrDA standard is going to install in a cellular phone, which make possible such an application as the credit settlement of accounts by the cellular phone and transmission of the advertisement and sales promotion information on it.

In recent years, the data-transmission speed exceeding 100 Mbps becomes needed in the use, since the exchanges of still pictures and video data taken by a digital camera are quickly expanded between mobile PCs and Audio-Video devices. The Ultra Fast IR Special Interest Group (UFIR SIG) is seated in the IrDA in 2002 to examine a physical layer corresponding to such a high speed connection. In order to realize the access speed higher than 100 Mbps and low power consumption and to secure the safety for eyes, the infrared transmission system using an eye safe semiconductor laser replaced with the conventional LED is developed, and it is proposed to UFIR standard⁽²³⁾.

Moreover, also about upper layers of the communication system

beyond 100 Mbps, IrBurst which is a high-speed infrared information transmission protocol on an IrDA standard is examined in order to transmit efficiently contents of digital images and movies⁽²⁴⁾. The high-speed infrared wireless communication is also considered in the application to the download service of such contents as music numbers and pictures to portable media players by a content-vending machine placed on a street⁽²³⁾⁽²⁴⁾.

4.3 Indoor Infrared Wireless Communication To advance the use of indoor infrared wireless connection, the Infrared Communication Systems Association (ICSA) provided the infrared wireless communication standard of 10 Mbps and 30 m-link distance in 1997 as ARIB STD-T50, where ARIB is an acronym of Association of Radio Industries and Businesses. Moreover, this standard has been expanded up to 100 Mbps in 2002. Then, further, the research and development of an infrared transmission system with data transmission rate beyond 1 Gbps are progressing, towards the use of wireless connection between LAN ports, PCs, audio-visual equipments as tuners and displays, and the examination to standardization is performed in the ICSA.

4.4 Outdoor Infrared Wireless Communication The present trend of development and use of an outdoor high-speed infrared wireless network system has not changed a lot with the place summarized in Ref. (25). The infrared wireless communication of the short distance type (<300 m, 100 Mbps) and of the long distance type of 1.25 Gbps/2.5 Gbps already put in practical use, and further, it will offer the relay connection of gaps between two fiber-optic networks and also supply the flexible large-data optical-communications link at a low cost. "The fiber-space hybrid light transmission technology" which utilizes the optical-communication technology of 1.5 μm band has been studied for this purpose, and direct transmission of 2.5 Gbps $\times$ 5 waves is experimentally proved at a distance of 200 m by the dense-wavelength-division-multiplexing (DWDM) technique, which can also view terabit transmission⁽²⁶⁾.

The infrared wireless communications are also expected to spread the use in image transmission systems for broadcast and the intelligent transport system (ITS) as well as walking support by the infrared audio communication to a pedestrian with visual impairment^{(27),(28)}.

4.5 Sub-terahertz Wireless Communication High-speed (10 Gbps) wireless communications with sub-terahertz carrier wave (120 GHz) which is much longer wavelength than infrared is developed by using high-speed repetition optical pulse generation technique and a Uni-Traveling-Carrier-Photodiode (UTC-PD) as a photon-to-electron conversion device in 1.5 μm band of the optical communication wavelength⁽²⁹⁾.

The sub-terahertz wave differs greatly in atmospheric transmission characteristics from the infrared, although both of them can realize the high-speed communications of the same level. The attenuation by absorption of water vapor and oxygen molecules in sub-terahertz is large as compared with infrared rays, but the attenuation by fog and haze is about two orders of magnitude as low as the infrared. The influence of rain has almost the same between them.

The sub-terahertz wireless communication system is expected in the use of the outdoor high-speed communication of a distance to 1 km such as a link between a TV-camera and a relay station of High Definition TeleVision (HDTV).

4.6 Space Optical Communication The optical communication in space which are links between satellites and

between a satellite and the ground have an advantage in high-speed and large-data transmission, small and lightweight hardware, and high secrecy compared with the radio waves. After the start of research of the 1960s in U.S., the optical communication technology in the space including highly precise capture, pointing and tracking technique onboard a satellite is continuously developed and accumulated, and in recent years the demonstration of communication experiments in the space has come to be carried out by U.S., Europe, and Japan. Please consult to Ref. (30) about the detailed explanations of this section.

The world first optical communication between satellites was successful in 2001 between the Semiconductor laser Inter-satellite Link EXperiment (SILEX) equipment of European satellite ARTEMIS and the low-altitude earth-orbit satellite SPOT-4. The inter-satellite optical communication experiment by international collaboration has successfully conducted between the European SILEX and the Japanese Laser Utilizing Communications Equipment (LUCE) onboard the OICETS in 2005.

4.7 Devices for Infrared Wireless Communication

Technical demand items to emitters for the infrared wireless communication are high output power, high-speed operation, and eye safety etc. The demands required to detectors are high-speed response and large sensitive area to hold a margin against to beam-dancing due to atmospheric turbulence.

The emitters to be developed are a high-speed infrared light emitting diode (LED), a super-luminescent diode (SLD), a vertical cavity surface emitting laser (VCSEL) and an eye-safe high-output laser diode (LD). As for the detectors, there have been developed a PIN-PD and an avalanche photodiode (APD) of Si which has sensitivity in 0.8 to 1- μm band and an InGaAs-APD of 1.3- μm band. These are discussed in detail by Ref. (31).

Moreover, fluoride-material fiber laser and amplifier in a wavelength region of 2 μm or longer are studied as a possible light emitter⁽³²⁾.

4.8 Safety Standard of Laser Light In the infrared wireless communication, since light from LDs or LEDs is emitted to the free-space, it is required to secure the safety especially to eyes when the light is exposed to a human body. As for the international safety standard on laser radiation, the standard documents "IEC 60825 series" are published by IEC (International Electrotechnical Commission). The IEC 60825-12 has examined about "the safety of an optical free-space communications system." For details, please consult to Ref. (33). The safety of LED basically follows the case of semiconductor lasers, although a compensation coefficient is applied to it since the light source size spreads.

5. Environmental Technology

The word of "environment" is used for very wide range such as space, atmosphere, earth, urban, human life, and so on. There are various phenomena with respect to the infrared in the field of environment where the various kinds of measuring technique are also there.

The infrared radiation in the space is measured by a telescope from the top of a mountain, plane or artificial satellite. Especially middle- and far-infrared radiation is observed from the satellite because of the atmospheric absorption. Near-infrared (0.75~2.5 μm) and middle-infrared (2.5~30 μm) sensors for the observation of space are supplied mainly by Rockwell Co. and Raytheon Co., respectively, and far-infrared sensor in the

wavelength longer than 50 μm is developed by each researcher who needs it⁽³⁴⁾.

The ways to observe the infrared radiation for the environment of the earth are divided mainly into three; the measurements of (1) reflection spectrum of the sun shine by the earth surface, (2) radiation spectrum from the earth surface, and (3) absorption spectrum of atmosphere⁽³⁵⁾. The atmospheric window is in the wavelength range from 8 to 14 μm . The radiation in this region is also called thermal infrared which is used for the estimation of the surface temperature of the earth. If an infrared thermal scanner or imager is used, it will be able to present a visible image of two-dimensional environmental information on the surface of the earth. Artificial satellites such as Landsat, NOAA, ADEOS etc. mount an infrared sensor to observe the surface of the ocean, the ground, the forestzone, etc. Their temperature distributions are generally measured by a split-window method which combines linearly the brightness temperatures in two spectral channels in the atmospheric window. The infrared radiation from the earth contains various information about the radiation from the earth-surface, and the radiation/absorption of atmosphere, aerosol, cloud etc. The spectrum analysis of the observed infrared radiation by using a proper spectrometer also presents not only the altitude profile of the temperature but also the density of gas such as O_3 , HNO_3 , NO_2 , CH_4 CFCs, etc.

Although urban heat island phenomenon is also seen by an infrared image from a satellite, it is observed in the detail by the measurement from an plane. It is important to know the land cover distribution such as buildings, pavement, green area, nude ground, etc. for analysis of urban environment and disaster prevention. Therefore precise mapping method of the land cover of urban area is investigated by the integration of airborne remote sensing data and geographical information system (GIS) data⁽³⁶⁾. It is confirmed by the thermal infrared image that the heat island phenomenon is seen not only in a big city but also in a countryside.

On the other hand it is also important to estimate from the view-point of the thermal environment in life space. In this case, the surface temperature distribution of the ground and the thermal field radiated to the human body should be estimated by observing all thermal radiation flux from solid angle of 4π . Mean radiant temperature is evaluated from the spherical thermograph. Thermal comfort of a humanbody is affected by air temperature, mean radiant temperature, air velocity and humidity. If there is not almost air movement around the human body, the mean radiant temperature gives an effect to the comfort with as degree as the air temperature.

Environmental pollution of atmosphere, river, ocean and soil is serious problem to be solved on a whole earth scale. Before considering it, we have to investigate the extent of the pollution. Spectroscopical infrared technology is useful for it because the pollution material has the inherent absorption spectrum in the infrared and is measured without destruction of the target⁽³⁷⁾. Environmental standard of air, for example, is established for SO_2 , CO , NO_2 , photochemical oxydant and floating particles in air. Infrared absorption method is applied generally to the measurement of SO_2 , CO and NO_x . A non-dispersive infrared gas analyzer is one of the most convenient instruments in which the same gas as the component in the object gas is used as a filter. The use of a front-rear chamber type detector sometimes suppresses interference between coexisting gasses such as CO and

CO_2 . The non-dispersive infrared gas analyzer is the most conventional but it is not possible to analyze simultaneously multiple components of gasses. Therefore an infrared spectrometer is also very often applied to qualitative and quantitative analysis of gasses. Fourier transform infrared spectrometer (FTIR) among some kinds of spectrometers has been utilized for various environmental researches for the microanalysis of atmospheric gas, accumulated materials at a river-mouth, pesticide residues on vegetables, etc.

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