Optical-Microwave Converter: Superconductor/Photomixer Hybrid System

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Abstract — **A new type of optical-microwave converter utilizing a photomixer and a high-T_C Josephson junction detector has been developed. The frequency difference of two laser beams has been observed in the characteristic of the high-T_C Josephson junction detector. The measured response of the detector for the microwave generated by photomixing two lasers suggests that the system can work as a highly sensitive wavelength meter with accuracy of ±3.5 pm. The system operation up to 20 GHz was also demonstrated by changing the wavelength of two laser beams.**

I. Introduction

Photomixers made of photoconductive materials such as photoconductive switch or photodiode have been developed as one of promising devices for microwave oscillators because of its high frequency range tunability and stability [1]-[5]. The photomixer illuminated by two different wavelength lasers generates coherent microwave that have a frequency component corresponding to the frequency difference of the two lasers. On the other hand, high-T_C Josephson junction is widely known as a very sensitive spectrometer in the frequency region of several tens GHz.

In the present work, we developed and demonstrated a new type of wavelength monitoring system based on optical-microwave conversion system that utilizes a photomixer and a high-T_C Josephson junction detector. The system can be used as a highly sensitive wavelength monitoring system for 1.55-μm lasers, which are widely, used in optical communication systems, where high sensitive monitoring and real time control of laser wavelength is critical issue.

II. Basic Idea of the System

Figure 1 indicates the basic idea of the system. Two lasers consisting slightly misaligned wavelengths λ_1 and λ_2 are mixed in an optical fiber system, and then formed optical beat was modulated in intensity at the frequency difference Δf of two lasers. The optical intensity I(t) of the optical beam is give by,

$$I(t) = I_{const.} \cos(\Delta f\, t + \phi) \text{ and,} \tag{1}$$

$$\Delta f = |c/\lambda_1 - c/\lambda_2| \tag{2}$$

where $I_{const.}$ is the maximum intensity of the optical beam and ϕ, c, and t indicate the phase constant, speed of light, and time, respectively. When the optical beam was introduced into the biased photomixer, the microwave corresponding to frequency difference is generated in the photomixer. The electric field of microwave $E(t)$ is directly proportional to the optical intensity, and is given by,

$$E(t) \propto I(t) \propto E_{const.} \cos(\Delta f\, t + \phi), \tag{3}$$

where $E_{const.}$ is the maximum amplitude of the microwave. The frequency of the generated microwave is detected by step-like current-voltage (I-V) curve (Shapiro steps) of a high-T_C Josephson junction detector. The voltage interval ΔV of Shapiro steps is directly related with the frequency of microwave Δf only by the fundamental physical constants as follow,

$$\Delta V = (h/2e) \times \Delta f, \tag{4}$$

where h and e are Plank's constant and elementary charge, respectively. Therefore, if the wavelength of the one laser (λ_1) is fixed as the reference, the wavelength of another laser can be determined by measured ΔV using the following equation,

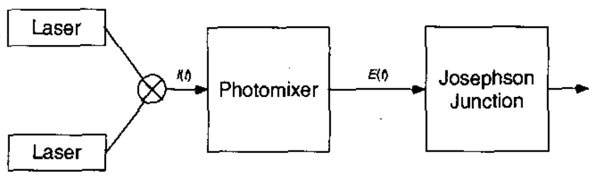

Fig. 1. The basic idea of the system, $I(t)$ and $E(t)$ is the optical intensity of a laser beat and the amplitude of a microwave. ΔV is Shapiro step interval of a Josephson junction detector.

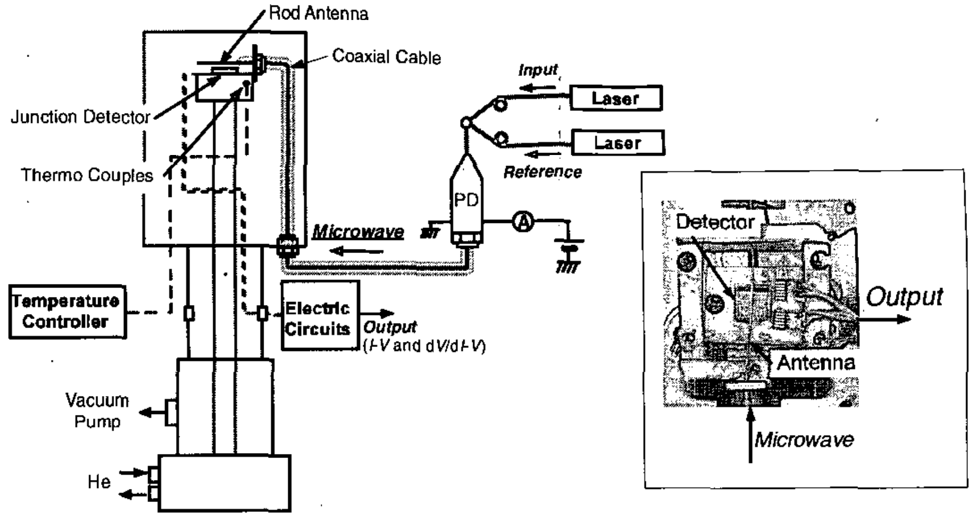

Fig. 2. Schematic diagram of our new system and photo image of the Josephson junction detector mounted on the cold finger of the cryostat (inset). A rod antenna was placed 1 mm above the detector.

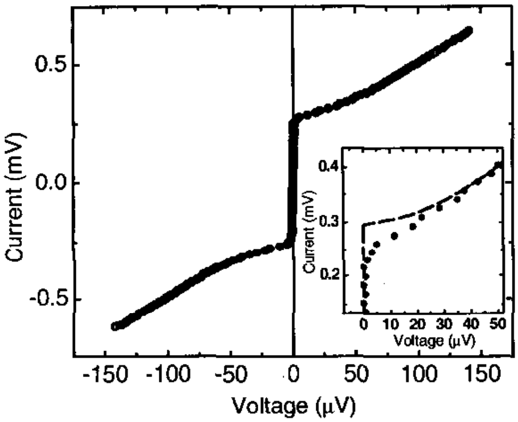

Fig. 3. Typical current–voltage (*I-V*) characteristics of the Josephson junction detector measured at 21 K. Inset is the enlargement of the figure. Closed circles are measured data and dashed line is theoretical carve calculated by resistive shunted junction model.

$$\lambda_2 = c \,/\, [\, c/\lambda_1 \pm (2e/h)\Delta V \,]. \tag{5}$$

III. Experimental Setup

Two single mode distributed feedback (DFB) lasers were used as optical sources. The maximum optical output power from laser sources was about 20 mW. The wavelength of two lasers could be tuned between 1530.0 nm and 1570.0 nm by changing operation temperatures of lasers. The photodiode that can operate up to 40 GHz was employed as a photomixer. The schematic diagram of the system is illustrated in Fig. 2. The microwave generated in the photodiode was coupled to a high-T_C Josephson junction detector, fixed inside a closed-cycle He cryostat, by a simple rod antenna (inset Fig. 2.) through semi-rigid coaxial cables. The Josephson junction detector was made of the *c*-axis oriented 100-nm-thick $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film deposited on a (100) MgO bicrystal substrate. The YBCO thin film was patterned into the simple strip line of the width 3 μm and length 20 μm using conventional argon ion dry etching technique. The grain boundary of the junction was formed at the center part of the strip line. The coupling rod antenna was 30 mm in length and was fixed about 1.0 mm above the Josephson junction detector. In this configuration, the direction of the electric field of the radiated microwave was parallel to the center strip of the Josephson junction, so that an effective coupling of the radiated microwave from antenna to detector was expected.

IV. Results and Discussion

A typical current-voltage (*I-V*) characteristic of the Josephson junction detector at temperature 21 K is shown in Fig. 3. The critical current I_C was about 240 μA and the value of $I_C R_N$ product (critical current times normal resistance) was about 41 μV. Inset in Fig. 3(a) provides an enlarge view of the measured (*I-V*) characteristics.

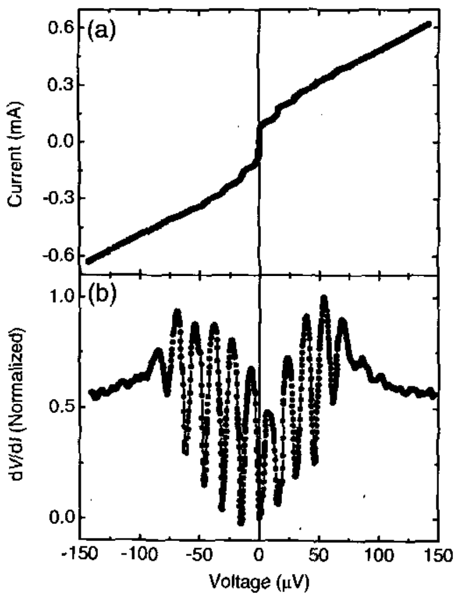

Fig. 4. (a) Current-voltage (I-V) and (b) deference resistance-voltage (dV/dI) characteristics of the Josephson junction detector with introducing the two laser beams into the photodiode. The dV/dI-V curve was normalized by the maximum peak.

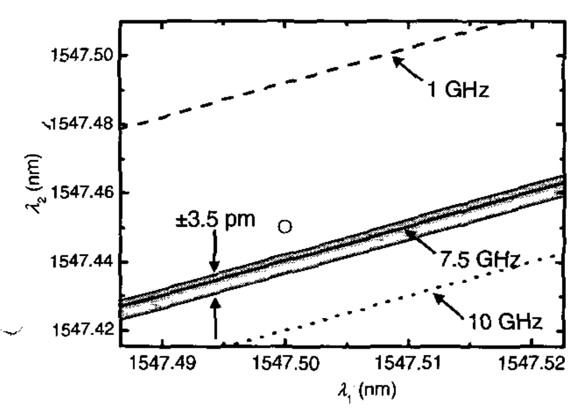

Fig. 5. Relation between the wavelength of two lasers and the frequency of generated microwave Δf. Dashed and dotted lines correspond to 1 GHz and 10 GHz, respectively. Solid line indicates the frequency measured from Shapiro step intervals in Fig. 4(a). The variation of the measured Δf is indicated by gray region. Open circle is the wavelength of two lasers used in Fig. 4. (Note that the wavelength of lasers was measured by commercial wavelength meter.)

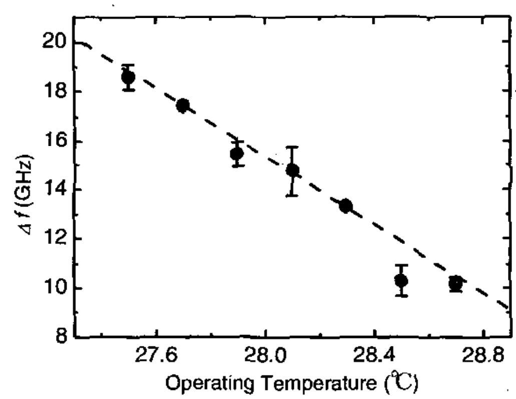

Fig. 6. Obtained Δf as a function of the operating temperatures of one laser. Changing the temperatures corresponds to changing the wavelength of the laser λ_2. Linear fit of the data was indicated by dashed line.

Closed circles are measured data and dashed line is the curve calculated by the resistive shunted junction (RSJ) model. Though the measured data almost agree with RSJ model, a slight deviation from the model can be seen around the transition point to the normal state. The deviation may be attributed to the thermal and surrounding noise of our system.

Figure 4 shows (a) I-V and (b) dV/dI-V characteristic of the detector, temperature at 21 K, measured after introducing the two laser beams into the biased photodiode. The wavelength of two lasers was λ_1 = 1547.5 nm and λ_2 = 1547.45 nm. The values of the wavelength were measured using a commercial wave-length meter with accuracy of ± 0.3 nm. The total output laser power was 14 mW. The frequency of generated microwave was successfully observed in the I-V characteristics of the detector as Shapiro steps (Fig. 4(a)). The negative peaks in dV/dI-V curve of Fig. 4(b) correspond to the Shapiro steps in I-V curve. The voltage interval ΔV of steps was around 15.5 μV, which corresponds to the microwave frequency Δf of about 7.5 GHz. We also observed high order steps up to 40 GHz in our experiment. The variation of Δf obtained from the higher order steps was between 7.2 GHz and 8 GHz in our experiments. Relation between the wavelength of two lasers and the frequency of generated microwave Δf is shown in Fig. 5. The generated Δf has linear dependence on the wavelength of two lasers, Eq. (2), therefore, Δf corresponding to any frequency can be linearly drawn by tuning the wavelengths of the lasers. For example, calculated Δf = 1 GHz and 10 GHz, respectively, are plotted by dashed and dotted lines in Fig. 5. Solid line, in Fig. 5, indicates the frequency measured from Shapiro step intervals, shown in Fig. 4(a) (Δf = 7.5 GHz). The variation of measured Δf is also shown as gray region. The wavelength of two lasers monitored by a commercial wavelength meter is plotted by open circle. The wavelength measured by commercial wavelength meter is slightly different from measured Δf, because of poor accuracy of the wavelength meter. Fig.5 suggests that the wavelength λ_2 of a laser can be measured with the accuracy of ± 3.5 pm (± 3.5 × 10^{-12} m) when wavelength λ_1 another laser is accurately known that can be achieved by using stable lasers such as the system based on a two-photon transition of rubidium atoms [6], [7]. It is expected that the accuracy can be further enhanced by two orders of magnitude by using series array of junctions as a detector, which will increase the output voltage ΔV [8]. Another feature of the present system is that it can realize high-speed-readout in comparison with commercial interferometer type systems.

Fig. 6 shows the measured Δf by the detector as a function of the operating temperature of one of the laser. Change in the operation temperature of laser causes a change in the wavelength of laser, which reflects in measured Δf. We fixed the operation temperature of one laser at 27.0 °C (λ_1 = 1547.7 ± 0.3 nm), and then measured the Δf by changing the operation temperature of another laser between 27.3 °C and 28.7 °C (λ_2 varies from 1547.25 ± 0.3 nm to 1547.65 ± 0.3 nm.). The measurement of Δf was carried out up to 20 GHz that was found to be directly proportional to the operation temperature with the proportionality coefficient of 6.9 GHz/°C. The frequency of measurement was limited by coaxial cables used at present system, which can be overcome by employing a photomixer/superconductor multilayer system [9] or using a uni-traveling-carrier photodiode (UTC-PD) [10] as a photomixer [11].

V. Summary

A new optical-microwave conversion system based on photomixing techniques is realized. The system utilizes a photomixer and a high-T_C superconductor Josephson junction detector. Optical information was successfully converted to the electric information using the system. The measurement results show that this system can be used as a wavelength meter with a very high accuracy of ± 0.3 pm that is comparable to the interferometer type system. We demonstrated the system operation up to 20 GHz, and the further work to overcome the frequency limit and enhancement in the accuracy by using series of array Josephson junctions is in progress.

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