Coherent synthesis of two continuous microwave signals generated by two optical beats

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Abstract: Two continuous 6-GHz signals were spatially synthesized by two optical beats, so that the microwave power was increased by 6 dB. Time delay difference between two optical beats were adjusted by altering the SMF length or LD wavelength. Also two continuous 20-GHz signals were synthesized by two optical beats and detected by Schottky Barrier Diode. Frequency of the synthesized 20-GHz signal was estimated from the measured time delay difference between two optical beats.

Keywords: optical beat, coherent synthesis, spatial synthesis, continuous wave, laser diode, microwave photonics

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Power increase of THz continuous-wave generated by optical beat is an important issue to apply the THz continuous-wave to imaging, spectroscopic system, communications, etc [1, 2, 3, 4]. Analysis and design of photomixer array is also studied as a way to increase the THz radiation power [5]. Here we coherently synthesize two continuous microwave signals generated by two optical beats for the enhancement of the microwave power. Experiments of coherent microwave synthesis by optical beats were carried out to obtain solid data toward future spatial synthesis of THz continuous-wave as shown in Fig. 1.

![Diagram of THz continuous-wave generation by optical beats](image)

Fig. 1. Picture of spatially synthesis of THz continuous-wave generated by optical beats.

2 Coherent synthesis of continuous 6-GHz signals by two optical beats

In order to generate two coherent microwave signals, we divided one optical beat using two distributed feedback laser diodes (DFB-LDs) into two coherent beats by optical divider as shown in Fig. 2. Microwave frequency is fixed to 6 GHz by adjustment of each LD wavelength, $\lambda_1$ and $\lambda_2$. In addition, the length of a standard single-mode fiber (SMF) was altered to adjust time delay difference between two coherent optical beats. Two continuous 6-GHz signals detected by each photodiode (PD) were combined by microwave divider. The power of the synthesized 6-GHz signal were measured using microwave spectrum analyzer.

![Diagram of coherent synthesis experiment](image)

Fig. 2. Schematic diagram of coherent synthesis experiment by altering the SMF length.
Comparison of power and spectrum of the synthesized 6-GHz signal by two optical beats was shown in Fig. 3. Coherently synthesized 6-GHz signal with in-phase and reversed-phase were compared with a 6-GHz signal generated by one optical beat. Power of coherently synthesized 6-GHz signal with in-phase was increased by almost 6 dB compared to that of a 6-GHz signal by one optical beat as shown in Figs. 3(a) and (b). Also coherently synthesized 6-GHz signal with reversed-phase was cancelled each other and decreased to the level less than that of a 6-GHz signal as shown in Fig. 3(c).

Fig. 3. Coherently-synthesized 6-GHz signal, (a) by one optical beat, (b) with in-phase by two optical beats, (c) with reversed-phase by two optical beats.

Next, two continuous 6-GHz signals detected by each photodiode were synthesized spatially. 6-GHz dipole antennas were used for both transmitting and receiving with horizontal polarization at a distance of 3 cm as shown in Fig. 4. Comparison of power and spectrum of the spatially synthesized 6-GHz signals were shown in Fig. 5. Power of 6-GHz signal with in-phase was increased by almost 5 dB compared to that generated by one optical beat as shown in Figs. 5(a) and (b). 6-GHz signal with reversed-phase was decreased by 6.5 dB less than that by one optical beat as shown in Fig. 5(c).

Fig. 4. Schematic diagram of spatial synthesis experiment.

In order to alter the SMF length to adjust the time delay difference between two optical beats, the SMF with different length needs to be replaced. On the other hand, adjustment of LD wavelength using the LD temperature control is able to adjust the time delay difference between two optical beats more easily and precisely than the SMF length adjustment.
Wavelength of LD1, $\lambda_1$, was fixed and wavelength of LD2, $\lambda_2$, was altered to adjust the time delay difference between two optical beats as shown in Fig. 6.

Fig. 7 shows synthesized power and frequency of microwave signal, MW1+MW2, when the wavelength of LD2, $\lambda_2$, was altered. Synthesized frequency is changed as the LD wavelength is altered. The power of synthe-
sized microwave signal is compared with that of each microwave signal, MW1 or MW2. Synthesized microwave power was increased by almost 6 dB than that of each microwave signal when the LD wavelength is adjusted to be cancelled the time delay difference between two optical beats. Also calculated microwave power based on the measured time delay difference between two optical beats is shown in the figure. As details of the calculation is shown in the next section, synthesized microwave power is periodically altered due to the time delay difference. Fig. 8 shows microwave spectrum of the synthesized continuous signal with in-phase and reversed-phase. Dynamic range of more than 20 dB in microwave power was realized by the LD wavelength adjustment (See in Figs. 7 and 8).

![Microwave spectrum synthesized by LD wavelength adjustment](image)

Fig. 8. Microwave spectrum synthesized by LD wavelength adjustment, (a) reversed-phase ($f = 6.435$ GHz), (b) in-phase ($f = 6.700$ GHz), (c) reversed-phase ($f = 7.135$ GHz).

### 3 Coherent synthesis of continuous 20-GHz signals by two optical beats

Continuous 20-GHz signals were coherently synthesized by two optical beats and detected by Schottky Barrier Diode (SBD) detector instead of microwave spectrum analyzer as shown in Fig. 9.

![Schematic diagram of coherent synthesis of 20-GHz signal detected by SBD](image)

Fig. 9. Schematic diagram of coherent synthesis of 20-GHz signal detected by SBD.
Since exact frequency of the detected signal cannot be measured generally in the higher frequency range like THz signal, we estimated the microwave frequency at around 20 GHz from the interference pattern of the detected power by SBD when LD wavelength was adjusted for coherent synthesis. When $\lambda_1$ was fixed and $\lambda_2$ was altered, synthesized microwave power was periodically changed as shown in Fig. 10. The cycle of the interference pattern is calculated from the time delay difference, $\tau$, between two optical beats. We may express wavelength difference, $\Delta \lambda$, between null points of the interference pattern as

$$\Delta \lambda = \frac{\lambda_2^2}{\tau c \pm \lambda_2},$$

where $\tau$ is the time delay difference between two optical beats and $c$ is the velocity of light. Since the time delay difference, $\tau$, between two optical beats is independent of synthesized microwave frequency, we measured the time delay difference, $\tau$, at around 7 GHz by using microwave spectrum analyzer before 20-GHz synthesis experiments by using SBD. Fig. 11 shows measured power and estimated frequency of synthesized signal at around 20 GHz when the wavelength of LD2 is altered. Measured null point of the synthesized

Fig. 10. Synthesized microwave power when LD wavelength is adjusted.

Fig. 11. Power and frequency of synthesized 20-GHz continuous signal when the wavelength of LD2 was altered.
power at around 21 GHz was made coincided with that of calculated interference pattern based on the measured time delay difference. Measured frequency of the synthesized signal was able to be estimated owing to comparison of the measured null point with calculated one obtained from the measured time delay difference, \( \tau \), between two optical beats (See in Fig. 11). In addition, measured power of synthesized microwave signal, MW1+MW2, is compared with that of each microwave signal, MW1 or MW2. Synthesized power was increased by around 4 dB compared to that of each microwave signal. Although microwave signal at around 20 GHz was coherently synthesized by two optical beats, the power increment, 4 dB, is considered to be lower than the theoretical value, 6 dB, because of inaccuracy of detected signal level of the SBD.

4 Conclusion

In order to increase the power of continuous-wave signal generated by optical beat, continuous 6-GHz signal was coherently synthesized with in-phase and reversed-phase by two optical beats. The continuous 6-GHz signal was synthesized spatially by adjustment of SMF length or DFB-LD wavelength. Measured power of 6-GHz signal synthesized with in-phase was increased by almost 6 dB compared to that generated by one optical beat. On the other hand, measured power of 6-GHz signal with reversed-phase was cancelled each other. Furthermore, continuous 20-GHz signal was coherently synthesized by two optical beats and detected by SBD detector. Measured power of 20-GHz signal synthesized with in-phase was increased by around 4 dB compared to that generated by one optical beat. Moreover, measured frequency at around 20 GHz was estimated when the microwave signal was detected by SBD. Frequency of the synthesized continuous signal by two optical beats was estimated owing to comparison of the measured null point of the synthesized power with calculated one obtained from the measured time delay difference between two optical beats.