Sub-THz Carrier Frequency Generation Stabilized by Mach-Zehnder Interferometric Phase Detection Scheme

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Abstract: We propose a Mach-Zehnder interferometric phase detection for low phase noise sub-terahertz (THz) carrier frequency generation. In this scheme, phase fluctuation between two optical signals can be detected as the interference between their optical sidebands. Experimental result shows that, by controlling the interference to be constant, the phase noise is successfully reduced, which indicates effectiveness of the proposed method.

Introduction: For sub-terahertz (THz) wireless communications, high carrier frequency generation with two different optical frequencies extracted by an arrayed-waveguide grating (AWG) filter from an optical frequency comb (OFC) has attracted a great deal of interest.[1,2] For reducing a phase noise of sub-THz carrier, the difference of optical path lengths between two optical frequencies should be detected and controlled to be constant. One of the approaches for detecting the difference of two optical path lengths is to dither optical path lengths and deduce relative optical phase fluctuations.[1] Recently, we have proposed another approach in which two optical paths configure a Mach-Zehnder interferometer (MZI) and the interference of an additional lightwave is detected as the relative optical phase fluctuation.[3] We demonstrated in this approach that the phase noise could be reduced at a generation of 50 GHz carrier frequency. In this paper, further developing the interferometric phase detection method, we proposed a simple and practical phase detection scheme without any additional lightwave and successfully demonstrated the phase stabilization at the generation of a 300 GHz carrier frequency.

Phase stabilization system: Figure 1 shows the conceptual diagram of the sub-THz wave generation system with our proposed phase detection scheme in which two optical paths are configured as a MZI. The single-mode wave (the optical carrier frequency is f_0) output from a narrow linewidth laser is phase-modulated at the frequency f_{RF} with an electro-optic modulator (EOM1) to generate the OFC. The two optical signals of different frequencies (f_{-n} and f_{+n}) are extracted from the OFC by an AWG filter. Two optical fibers between the AWG filter and the 50:50 optical coupler (OC) are almost equal in their length in order to work as a kind of a MZI. Note that this configuration is not a conventional MZI because optical frequencies going through two optical paths are different and they never interfere with each other by themselves.

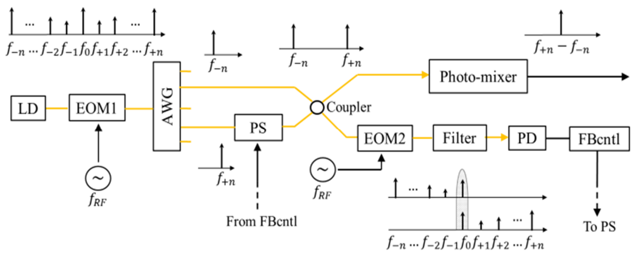

Fig. 1: Mach-Zehnder Interferometric phase stabilization scheme

Assuming f_{-n} is smaller by $n \times f_{RF}$ than f_0 and f_{+n} is larger by $n \times f_{RF}$ than f_0, their waves after the OC (F_{-n} and F_{+n}) could be expressed as follows using the Bessel function J_n:

$$F_{-n}(t) = J_{-n}(m)cos[2\pi f_0 t + (-n)2\pi f_{RF} t] \tag{1}$$

$$F_{+n}(t) = J_{+n}(m)cos[2\pi f_0 t + (+n)2\pi f_{RF} t \ + \ \Delta\varphi(t)] \tag{2}$$

where $\Delta\varphi$ is the phase difference between F_{-n} and F_{+n} which originates from the optical path length fluctuations between the AWG filter and the OC, and m is the modulation index which is proportional to the input voltage of EOM1. In our experiment, the voltage was set at such a value that $|J_{-n}|$ and $|J_{+n}|$ get maximum in order to obtain a large signal-to-noise ratio.

One set of optical signals from the optical coupler is input to the photo-mixer which generates the sub-THz beat frequency $(f_{+n} - f_{-n})$. The other set of optical signals is modulated with another electro-optic modulator (EOM2) at the same voltage and frequency as EOM1. As a result, the two optical signals generate the OFCs with an interval of f_{RF}, in which both the OFCs have the same optical frequencies of f_0. Thus, the optical wave (F_0^*) at the frequency f_0 is expressed as follows by using (1) and (2):

$$F_0^*(t) = J_{+n}(m)J_{-n}(m)\cos 2\pi f_0 t + J_{-n}(m)J_{+n}(m)\cos[2\pi f_0 t + \Delta\varphi(t)]. \tag{3}$$

This equation shows that F_0^* includes the phase fluctuation $\Delta\varphi$ between the two optical paths. Thus, we can detect $\Delta\varphi$ by monitoring the interference of F_0^*. To observe interference of F_0^*, we used an optical band-pass filter with the center frequency of f_0 and a photodiode (PD). As the interference after EOM2, the PD output voltage (V) is expressed as follows:

$$V \propto \sin\Delta\varphi(t). \tag{4}$$

The detected phase fluctuation is fed back to be constant using the phase shifter (PS) through PID controller, so as to stabilize the phase fluctuation of the sub-THz beat frequency.

Results and discussion: The laser output wave of $f_0 = 193.75$ THz was modulated with EOM1 at $f_{RF} = 25$ GHz and the voltage was set at such a value that $|J_{-6}|$ and $|J_{+6}|$ get maximum to generate the OFC. The AWG filter extracted -6th and 6th optical sidebands from the OFC. The photo-mixer generated a 300 GHz beat signal from these optical sidebands. EOM2 modulated the two sidebands at the same frequency as that of EOM1 to generate the optical frequencies of $f_0 = 193.75$ THz. The optical interference at f_0 was extracted by the optical band-pass filter and detected by the PD. The PD output voltage was fed back to the PS which consists of a piezo-electric device, so as to control the voltage to be constant. Figure 2(a) shows the PD output voltage without phase control observed at an oscilloscope. From equation (4), the output voltage fluctuation has a sinusoidal function with the phase fluctuation as a valuable. From this, we estimated that the voltage change of 260 mV corresponds to the phase fluctuation of π. Figure 2(b) shows the PD output voltage with phase control. The output voltage is stabilized so that the fluctuation is within ± 50 mV. This corresponds to phase stabilization with an accuracy of 0.2 π or less. Figure 3 shows the relative phase noise intensity spectra obtained by Fourier transform of the waveforms in Fig. 2(a) and (b). The phase noise in the region below 5 Hz decreases significantly with our phase stabilization system.

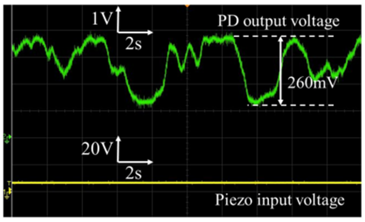

Fig. 2(a): Interfered light power without control

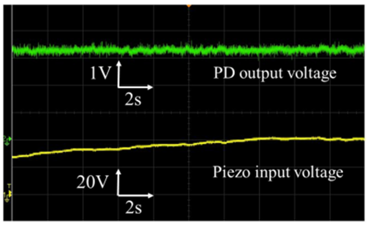

Fig. 2(b): Interfered light power with control

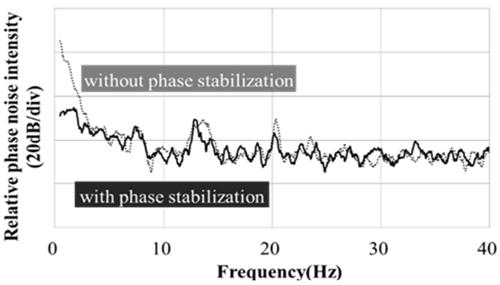

Fig. 3: Relative phase noise intensity spectra

Conclusions: We proposed and demonstrated the MZ interferometric phase detection scheme for low phase noise sub-THz carrier frequency generation. The phase fluctuation between two optical signals can be detected as the interference between their optical sidebands and successfully stabilized by a feedback controller.

Acknowledgement: The authors thank NTT Photonics Laboratories for their experimental support. This work was supported by the Strategic Information and Communications R&D Promotion Programme (SCOPE) 2013, from the Ministry of Internal Affairs and Communications, Japan.

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