THz wave generation using hybrid electro-optic modulators: simulations and experimental results

Sanghoon Chin
BU-I, Instrumentation
Centre Suisse d'Electronique et de Microtechnique (CSEM)
Neuchâtel, Switzerland
sanghoon.chin@csem.ch

Ewelina Obrzud
BU-I, Instrumentation
Centre Suisse d'Electronique et de Microtechnique (CSEM)
Neuchâtel, Switzerland
ewelina.obrzud@csem.ch

***Abstract*—A novel scheme to generate terahertz waves is proposed and numerically and experimentally investigated. The configuration of the proposed technique consists of cascaded electro-optic modulators to apply sinusoidal hybrid modulation of optical amplitude and phase onto the incident light. The key to drive an efficient terahertz wave relies on the spectral tuning capability of the optical spectrum of the modulated light. The optical power of sidebands around the optical frequency of the seed laser can be significantly reduced by optimizing the relative phase offset of microwave signal applied to the amplitude and phase modulation and the DC bias of amplitude modulator. In this way, a proof-of-concept dual frequency-like laser with a spectral distance of 86.4 GHz has been successfully generated.**

Keywords—microwave photonics, terahertz source, optical frequency comb, electro-optic modulator

I. INTRODUCTION

The generation of microwave and terahertz (THz) wave has been intensively investigated and rapidly developed thanks to the recent advancement of microwave photonics technology that improve multiple complex functions in radio-frequency engineering and creates novel opportunities by the wide bandwidth and low loss of modern photonics [1]. Especially, photonic techniques to generate THz wave signals have attracted great attention in the terahertz science community due to its unique properties. Since THz waves are the short wavelengths, they are inherently less susceptible to free-space diffraction and detrimental interference with neighboring antennas. Besides, they provide great resilience to eavesdropping as well as higher link directionality in compact footprints. Taking into account all those advantages, THz communication can supply large bandwidth and long-distance high-capacity services while satisfying requirements of the future sixth-generation (6G) communication (?) and beyond [2]. Another crucial application of THz wave relies on their unmatched capability of the non-destructive/non-invasive imaging. Since THz wave radiation is non-ionizing, it can penetrate optically opaque materials such as plastic, wood, paper and clothing. Consequently, THz imaging sensors can accurately diagnose and screen target objects secured in non-metallic containers without damaging them thanks to the low photon energy [3].

The most straightforward photonic scheme for generating microwave and THz band signals is realized based on directly modulated lasers. Electrical signals applied to the laser can be easily converted into optical signals to produce multiple harmonics of modulation frequency. However, soon it's been identified that the maximal achievable frequency of generated microwave signals is practically limited by the modulation rate and bandwidth of the employed laser [4,5]. An alternative method lies in the strength of optical heterodyne technique. The mutual interference between two separately operating lasers manifests a heterodyne beat signal at the photodetector output. The frequency of beat signal can be readily obtained over the terahertz band since the beat frequency is essentially determined by the differential optical frequency between the two lasers [6,7]. But, this scheme is hindered by the instability of the frequency interval between the two lasers and random optical phase fluctuations, necessitating a complex regulation procedure for phase de-correlation compensation between the lasers. For this reason, the two-color laser concept has been also actively studied to generate THz wave signals [8-10].

Among existing photonic methods for the generation of microwave and THz waves, the scheme utilizing the optical frequency comb has been considered a breakthrough solution, demonstrating the promising performance [11-15]. The combination of a single laser and multiple electro-optic modulators (EOM) in series provides an uncomplicated and economical architecture to effectively produce a wideband frequency comb covering THz range [16-22]. In turn, the direct optical heterodyne between optical comb lines through a photo-mixer in uni-traveling carrier photodiodes or high-speed p-i-n photodiodes enables to generate high-stable THz carriers.

In this paper, we propose a simple and robust technique to generate very high frequency carriers over sub-millimeter and THz range with low phase noise. This scheme makes use of spectral tailoring of optical spectrum generated by sinusoidal hybrid phase and amplitude modulation. The optical phase of a seed laser operating in the C-band is intensively modulated through a phase-EOM, resulting in a broadband optical frequency comb with line spacing equal to the modulation frequency. Then, the generated multicarrier is fed to an amplitude-EOM to reduce the optical power of comb lines around the seed laser frequency. Since the optical spectrum at the modulator output is determined by the superposition of two independent modulation patterns resulting from the phase and amplitude modulation respectively, the output spectrum can be altered as a function of relative phase of modulation applied to the two modulators and the DC bias position of amplitude-EOM. In most use cases, the role of amplitude-EOM is to generate a flat optical frequency comb. But, in this experiment the parameters of amplitude-EOM are optimized to suppress a large number of sidebands around the center frequency; hence, producing a two color-like light source. Moreover, the relative frequency of the two tones can be adjusted by the RF power to the phase-EOM, showing the tunability of the carrier frequency of the generated THz wave. For proof-of-concept, a dual frequency-like light source with a spectral spacing of 86.4 GHz is generated while modulating the concatenate EOMs at 10.8 GHz.

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II. PRINCIPLE OF OFC GENERATION

Figure 1 illustrates the simplified schematic diagram of conventional optical setup to generate wideband flat-top sidebands based on the sinusoidal hybrid modulation. Such broadband multicarrier generator mainly consists of a LiNbO$_3$ phase modulator, Mach-Zehnder intensity modulator, RF oscillator and RF phase shifter.

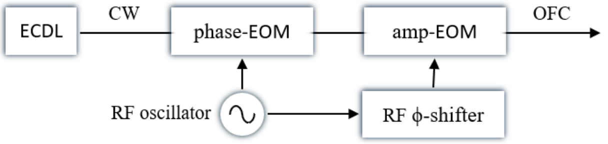

Fig. 1. Simplified schematic diagram to generate a wideband sidebands using sinusoidal hybrid modulation. CW: continuous wave. OFC: optical frequency comb.

When continuous wave light is fed into a phase-EOM, the phase-modulated light at the modulator output produces multiple sidebands at frequencies both below and above the optical frequency of the incident light; hence, resulting in an optical frequency comb (OFC). The frequency interval of adjacent comb lines is equal to the modulating RF frequency and the number of sidebands is determined by the RF power. In general, the optical power of the fundamental tone and the higher order sideband harmonics can be described by the Bessel function. It means that the amplitude of the generated sidebands cannot remain uniform across the entire OFC spectrum. However, notice that the light spectrum can be readily flattened by time-gating the phase modulated light, thus achieving hybrid phase and amplitude modulation. The electrical field as a result of the hybrid modulation is explicitly expressed as (1):

$$E_{out}(t) = e^{i2\pi v_c t} \cdot e^{iM_{dep}\sin(2\pi RFt)} \cdot \{\sin(2\pi RFt + \Delta\phi) + DC\} \quad (1)$$

where the first term represents the electrical field of the incident light, the second term corresponds to the phase modulation and the third terms accounts for the time gating of phase modulated light with the transmission position of intensity modulator adjusted by the DC bias. $\Delta\phi$ in the third term is the phase offset between the RF signal applied to the phase and amplitude modulator. In fact, the values of the phase offset and DC bias position are the key for the spectral tailoring of the OFC spectrum as will be discussed later.

III. EXPERIMENTAL RESULTS AND SIMULATIONS

In our experiment, a continuous wave (CW) laser operating at a wavelength of 1560 nm is strongly phase-modulated at 14.5 GHz with a modulation depth of >9, followed by an intensity modulation under conditions of $\Delta\phi$=0 and DC=1 (See (1)). The RF phase synchronization between the two modulators is precisely controlled using an RF phase shifter placed in front of amplitude-EOM. As shown in Figure 2(a), the hybrid modulation generates a presumably flat OFC over a spectral bandwidth of ~7 nm, and the measured spectrum shows a good agreement to the simulated spectrum obtained by (1). In Figure 2(b), it’s shown that only the time window, where the laser experiences the negative frequency chirp, is selected, which is the key configuration for obtaining a flattened comb spectrum. However, the optical power at the edge parts of the OFC is higher than the middle part. It is attributed to the phase modulation pattern that is sinusoidal, instead of parabolic. But, such nonlinearity can be mitigated by optimizing the operation parameters of the intensity modulator [19]. Nevertheless, the main advantage of this configuration lies in the capability of ultra-short optical pulse generation since the induced negative frequency chirp across the optical pulse can be effectively compensated by using a dispersive optical medium having opposite dispersion. In this manner the initially chirped pulse can be compressed in the time domain, ideally reaching the transform-limited pulse width if the frequency chirp induced by the hybrid modulation is perfectly linear.

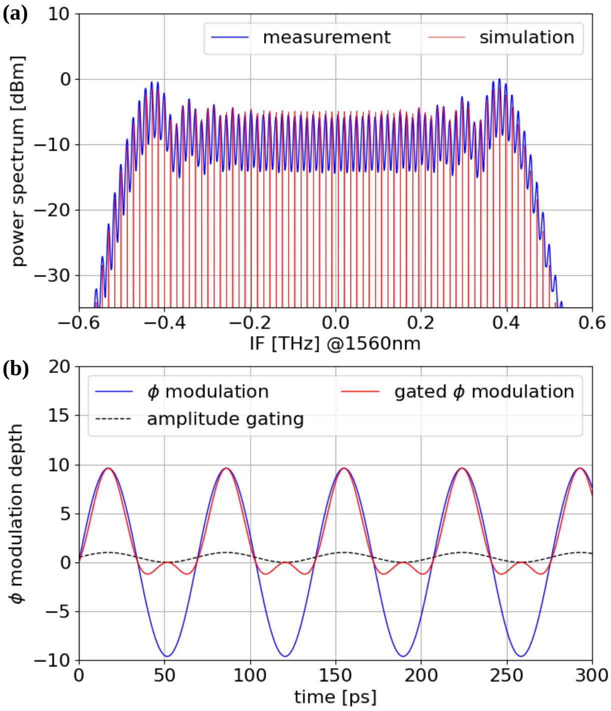

Fig. 2. (a) Comparison between the measured and simulated OFC generated by the hybrid modulation, showing a good agreement. (b) Illustration of time gating of phase modulation, selecting only the time window where the laser experiences negative frequency chirp.

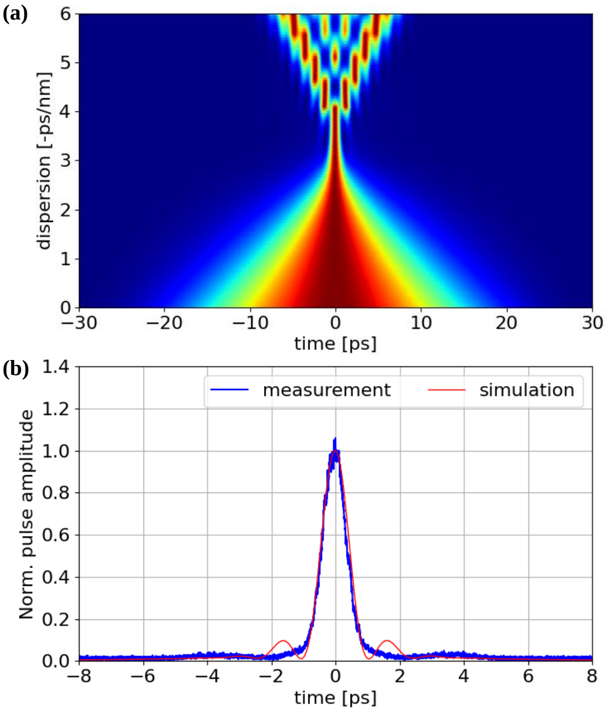

Fig. 3. (a) Simulation of compressed optical pulse with respect to dispersion parameter. (b) Comparison between the measured and simulated compressed pulse with duration of ~930 fs, showing a good agreement.

The temporal profile of the compressed pulse is simulated numerically as a function of the dispersion parameter, as shown in Figure 3(a). This is the process necessary to determine the required amount of dispersion for maximum temporal compression of the chirped pulse for a given modulation depth at the phase-EOM. The simulation indicates that the pulse width is continusouly reduced as the dispersion of optical medium increases up to -3.58 ps/nm, but begins to broaden once this value is exceeded as expected. Therefore, we used a chirped fiber Bragg grating as dispersive medium that has a dispersion parameter of ~3.6 ps/nm to generate the coherent optical frequency comb. The compressed optical pulse was then measured by an autocorrelator, as shown in Figure 3(b). The pulse width was measured to be 930 fs assuming a Gaussian profile, showing a very good agreement to the simulated compressed pulse.

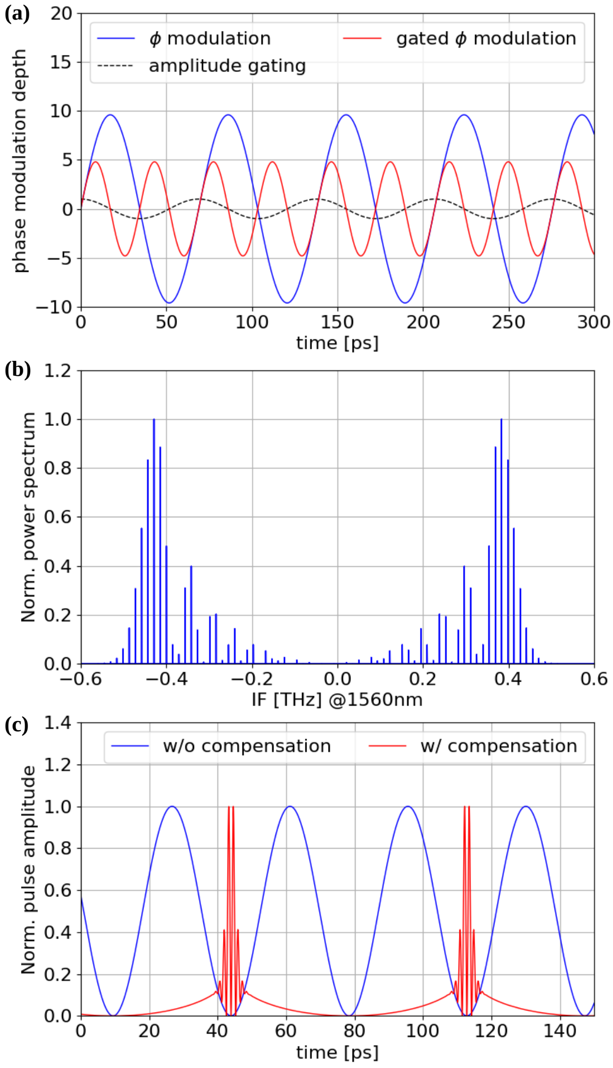

Fig. 4. Simulation results. (a) Time gating of phase modulation, generating two clock pulses by the specific DC position of amplitude-EOM. (b) Tailored spectrum reducing the optical power of sidebands in the middle of the OFC spectrum. (c) Generation of 3 ps THz wave optical pulse train after applying a dispersion compenstation of -5 ps/nm.

However, it is important to mention that slight changes in operation parameters of the intensity modulator provides a potential to generate an efficient THz wave pulse. The reason is that the output spectrum as a result of hybrid modulation is determined by the superposition of two clock pulse spectra induced by the operating DC bias position of the amplitude modulation [23]. Figure 4 demonstrates simulations results. When operating the intensity modulation with $\Delta\phi=\pi/2$ and DC=0, as shown in Figure 4(a) the flattened comb spectrum can be converted to a two color-like laser source, as shown in Figure 4(b) thanks to the significant optical power reduction in the middle part of the comb spectrum. It turns out that two packages of comb lines are found to remain at two extreme edges of the comb spectrum, respectively. However, due to the inevitable optical frequency chirp the intensity profile of the output signal follows the intensity modulation pattern, as shown in Figure 4(c). But, when an appropriate dispersion compensation, i.e., -5 ps/nm, is applied, all comb lines can become coherent to generate a 3 ps optical pulse train carrying a terahertz wave at 0.754 THz.

To validate the proposed technique, a phase-EOM was modulated at 10.8 GHz with a modulation dept of ~1 while an amplitude-EOM was operated with $\Delta\phi=\pi/2$ and DC=0. Note that such operation conditions were substantially limited by the availability of electro-optic and electrical components in our laboratory. However, we would like to emphasize that the experiment results demonstrate a good proof-of-concept, showing that comb lines are effectively suppressed in the middle part of the comb spectrum, as shown in Figure 5.

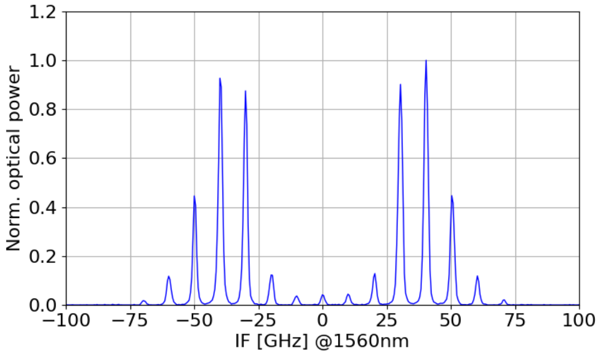

Fig. 5. Experimental demonstration of the generaton of two color-like light source by effectively suppressing optical powers in the middle part of the generated comb spectrum.

IV. CONCLUSIONS

In summary, a novel approach to realize a tunable THz wave generation based on hybrid modulation of light through a cascaded phase- and amplitude-EOMs is proposed and experimentally demonstrated. To verify the proof-of-concept, a dual frequency-like light source with a spectral spacing of 86.4 GHz has been successfully demonstrated. However, it must be noticed that the performance of the generated two-tone laser is not limited by fundamental physics, but limited by the experimental setup. In addition, more sophisticated modulation functions such as triangular-shape for phase modulation and rectangular-shape for amplitude modulation can be employed to produce better quality terahertz signals. We believe that the proposed method can pave the way to simplify the photonic architecture for the generation of THz wave while enhancing the high quality THz signals in terms of wide frequency tunability, spectral purity and phase noise.

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