Research on Opto-DMD Processor-Based Photonic Millimeter-Wave Generation Devices and Exploration of Broadcasting 5G Millimeter-Wave Deployment Scenarios (Postprint)

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Date: 2023-10-08T00:00:00+00:00

Abstract

This paper first briefly reviews the development of millimeter wave technology in terms of spectrum and industrial chain, then proposes a novel optically-generated millimeter-wave device based on Opto-DMD, which is capable of generating millimeter-wave signals in the 17.23GHz∼137.36GHz frequency band. Concurrently, a brief introduction to its core component, Opto-DMD, is provided. Subsequently, theoretical analysis is performed on the key processes involved in the optical millimeter-wave generation process, including the vernier effect, four-wave mixing, and optical heterodyning. Finally, the advantages and disadvantages of millimeter wave are analyzed, and deployment scenario recommendations for broadcasting and television 5G millimeter wave are presented.

Full Text

Preamble

Research on Opto-DMD Processor-Based Optical Millimeter-Wave Generation Device and Discussion on Broadcasting and Television 5G Millimeter-Wave Deployment Scenarios

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Abstract: This paper first briefly reviews the development status of millimeter-wave technology in terms of spectrum resources and industrial chain maturity. It then proposes a novel optical millimeter-wave generation device based on Opto-DMD (Opto-Digital Micromirror Device) capable of generating millimeter-wave signals in the 17.23GHz–137.36GHz frequency band, accompanied by a concise introduction to the core Opto-DMD component. Subsequently, key processes involved in optical millimeter-wave generation are theoretically analyzed, including the Vernier effect, four-wave mixing (FWM), and optical heterodyne method. Finally, the advantages and disadvantages of millimeter-wave technology are examined, and deployment scenario recommendations for broadcasting and television 5G millimeter-wave networks are proposed.

Keywords: optical millimeter-wave generation; 5G; Opto-DMD; Vernier effect; four-wave mixing; optical heterodyne method

Classification: TN294.3
Document Code: A
Article ID: 1671-0134(2021)07-149-05
DOI: 10.19483/j.cnki.11-4653/n.2021.07.046

Citation Format: Wang Tao, Zhang Jian. Research on Opto-DMD Processor-Based Optical Millimeter-Wave Generation Device and Discussion on Broadcasting and Television 5G Millimeter-Wave Deployment Scenarios [J]. China Media Technology, 2021(07): 149-153.

1. Opto-Digital Micromirror Device (Opto-DMD)

By the end of 2020, China had deployed over 718,000 5G base stations, predominantly operating in the FR1 band (450MHz-6GHz). While FR1 offers superior coverage, its data rate and capacity fall far short of ideal 5G metrics (e.g., peak rates of 20Gbps and latency below 1ms). Millimeter-wave, with its abundant contiguous spectrum resources, can better satisfy demanding 5G applications such as ultra-high-definition video, VR/AR, industrial automation, vehicle networking, subways, large sports venues, and conference centers. The 2019 World Radiocommunication Conference (WRC-19) reached consensus on 5G millimeter-wave spectrum allocation (approximately 17GHz), specifically including 24.25GHz-27.5GHz, 37GHz-43.5GHz, 45.5GHz-47GHz, 47.2GHz-48.2GHz, and 66GHz-71GHz, though the 45.5GHz-47GHz and 47.2GHz-48.2GHz bands are only used in certain countries and regions.

In July 2017, China' s Ministry of Industry and Information Technology (MIIT) designated the millimeter-wave bands 24.75GHz-27.5GHz and 37GHz-42.5GHz as 5G trial frequencies. In March 2020, MIIT issued a notice on accelerating 5G development, stating it would "release frequency usage plans for certain 5G millimeter-wave bands in a timely manner, and conduct research on dedicated frequency planning for 5G industries (including industrial internet), implementing technical trial frequency licenses when appropriate." With support across the entire industrial chain, millimeter-wave applications have achieved significant progress. However, compared to FR1, the millimeter-wave industrial chain remains immature, particularly regarding downstream terminals. Moreover, China's domestic capabilities in core components and chips still lag behind international levels, representing a notable gap.

The Opto-Digital Micromirror Device (Opto-DMD) is a semiconductor optical switch that integrates hundreds of thousands of physical square micro-mirrors onto a CMOS silicon substrate in an addressable array. Each micro-mirror represents one pixel with switching speeds exceeding 1,000 times per second. By controlling the hinge-like actuators beneath each mirror, the micro-mirrors can be rotated to different orientations (+12° and -12°), enabling independent control of each pixel. When incident light illuminates the Opto-DMD surface, digital drive signals from CMOS RAM apply addressing voltages to target micro-mirrors, driving them to rotate diagonally and independently. This causes diffraction of incident light at corresponding pixels, achieving optical filtering—reflecting desired light while absorbing undesired light via light traps.

The Opto-DMD chip used in this work measures 0.55 inches and comprises 1024$×$768 square micro-mirrors, each with dimensions of 10.8 µm × 10.8 µm. This paper leverages the diffraction effect of the Opto-DMD as a wavelength-selective filter in a 5G millimeter-wave generation experimental apparatus.

2. 5G Millimeter-Wave Generation Experimental Device and Principle

This paper proposes a novel optical millimeter-wave generation device based on an optoelectronic micromirror that can produce millimeter-wave signals from 17.23GHz to 137.36GHz (with 17.23GHz and 27.47GHz experimentally observed). This provides an optional solution for high-frequency millimeter-wave carrier signals required by 5G NR and demonstrates potential applications in microwave photonics, 5G fronthaul, and optical fiber sensing.

2.1 Experimental Device

[Figure 1: see original paper] illustrates the proposed 5G millimeter-wave generation experimental apparatus. In this architecture, the Opto-DMD and 1200 mm^{-1} blazed grating constitute the bulk optics section, while the fiber collimator, fiber coupler, and erbium-doped fiber amplifier (EDFA) comprise the fiber optics section. The EDFA generates and amplifies C-band (1530nm–1560nm) amplified spontaneous emission (ASE) spectrum. The 1200 mm^{-1} blazed grating primarily performs beam multiplexing and demultiplexing. The Opto-DMD selects dual wavelengths from the EDFA' s ASE by loading different addressing voltages onto pixel regions of its surface. Two secondary ring resonators constructed from single-mode fibers of different lengths (~1.9 meters and ~2.1 meters) and a primary ring resonator (~12.4 meters) utilize the Vernier effect to generate dual-wavelength single-longitudinal-mode laser output. High-nonlinearity photonic crystal fiber (nonlinear coefficient ~11 $W^{-1}km^{-1}$, flat dispersion coefficient ~1 ps/nm/km at 1550nm) employs four-wave mixing to achieve stable, uniform dual-wavelength single-longitudinal-mode laser output.

Each pixel of the 0.55-inch Opto-DMD corresponds to a wavelength variation of 0.055nm, meaning the Opto-DMD filter bandwidth can be considered 55pm (when selecting one pixel to represent the width of a two-dimensional grating).

Using formula (1), the filter bandwidth of the Opto-DMD at different center wavelengths can be obtained: at 1530nm center wavelength, the filter bandwidth is 7.05GHz; at 1560nm, it is 6.78GHz.

$$\text{Bandwidth} = \frac{c \cdot \Delta\lambda}{\lambda^2}$$

where c represents the speed of light (3$×10^{8}$ m/s) and λ is the center wavelength.

From the Vernier effect, as shown in formula (2), the longitudinal mode frequency spacing (i.e., free spectral range, FSR) of the composite ring resonator in Figure 1 is the least common multiple of the FSRs of the primary ring cavity and two secondary ring cavities [1]. As shown in formula (3), FSR is inversely proportional to the length of the fiber ring cavity [2]:

$$\text{FSR} = \frac{c}{nL}$$

where L is the fiber ring cavity length and n is the effective refractive index of the fiber loop, taken as 1.4468.

(1) Without the two secondary ring cavities, the experimental apparatus has only the primary ring resonator with a fiber length of 42.4 meters (including 30 meters of high-nonlinearity photonic crystal fiber). From formula (3), the FSR is 4.808MHz.

(2) With the two secondary ring cavities added, the fiber lengths are 1.9 meters and 2.1 meters, respectively. From formula (3), their FSRs are 107.56MHz and 97.31MHz, respectively.

According to the Vernier effect and combining formula (2), the composite ring resonator in this experimental apparatus achieves an FSR of 41.5GHz. This mode spacing is much larger than the Opto-DMD filter bandwidth at 1530nm and 1560nm, enabling single-longitudinal-mode laser generation.

2.4 Stable Single-Longitudinal-Mode Dual-Wavelength Laser Generation (Four-Wave Mixing Effect)

At room temperature, mode competition from the erbium-doped fiber (EDF) homogeneous gain medium causes unstable dual-wavelength laser output, which fails to meet the requirements for subsequent millimeter-wave signal generation. This experimental apparatus employs four-wave mixing (FWM) in high-nonlinearity photonic crystal fiber to redistribute energy between the dual wavelengths, reducing their power difference and ultimately achieving stable dual-wavelength output.

Assuming the dual-wavelength laser generated by the apparatus has wavelengths λ_1 and λ_2 with frequencies ω_1 and ω_2, the FWM effect is described by formulas (4) and (5), where ω_3 and ω_4 are newly generated frequencies:

$$\omega_3 = 2\omega_1 - \omega_2$$
$$\omega_4 = 2\omega_2 - \omega_1$$

Assuming the powers of lasers at frequencies ω_1 through ω_4 are P_1 through P_4, respectively, where P_3 and P_4 are [3]:

$$P_3 = \gamma L P_1^2 P_2$$
$$P_4 = \gamma L P_2^2 P_1$$

where γ represents the fiber nonlinear coefficient and L is the FWM interaction length.

During the experiment, the power variations at ω_1 and ω_2 are ΔP_1 and ΔP_2, respectively, resulting from power transfer from lasers at ω_2 and ω_1. As shown in formula (4), during stable dual-wavelength generation, photon annihilation at frequency ω_2 creates two photons at frequencies ω_3 and ω_2, with $\omega_3 \approx \omega_1$. Through continuous photon annihilation and creation, the power difference between the dual wavelengths gradually decreases.

To ensure stable millimeter-wave signal generation, the phase drift of the two input single-longitudinal-mode lasers must be sufficiently small and stable. In this apparatus, since both input lasers originate from the same source, their phase drift can be guaranteed to be small, while the introduction of high-nonlinearity photonic crystal fiber ensures that the phase drift remains stable.

Combining formulas (8) and (9) reveals:

$$\Delta P_1 = \gamma L P_2 (P_2 - P_1)$$
$$\Delta P_2 = \gamma L P_1 (P_1 - P_2)$$

From formula (10), when $\Delta P_1 > 0$, FWM transfers energy from the ω_2 laser to the ω_1 laser. Conversely, when $\Delta P_1 < 0$, energy transfers from the ω_1 laser to the ω_2 laser. Thus, FWM in the high-nonlinearity photonic crystal fiber effectively suppresses mode competition from EDF homogeneous gain, enabling highly stable single-longitudinal-mode dual-wavelength laser output that facilitates subsequent high-frequency millimeter-wave generation.

2.5 Optical Millimeter-Wave Generation (Optical Heterodyne Method)

Various methods exist for optical millimeter-wave generation; this paper employs the optical heterodyne method. Two single-longitudinal-mode lasers from the same source are input into a photodetector (PD, u2t photonics The Optilab PD-30 GHz) for beating, and the resulting signal is analyzed using an electrical spectrum analyzer (ESA, R&S FSV-30). The specific analysis is as follows.

The two single-longitudinal-mode lasers are expressed as [5]:

$$E_1(t) = \cos(\omega_1 t + \phi_1)$$
$$E_2(t) = \cos(\omega_2 t + \phi_2)$$

where ΔL_1 and ΔL_2 represent the optical path differences, and ϕ_{10} and ϕ_{20} represent the initial phases. When the two lasers beat on the PD, their intensities superimpose:

$$I(t) = \langle [E_1(t)+E_2(t)]^2 \rangle = 1+\frac{1}{2}\cos(2\omega_1 t+2\phi_1)+\frac{1}{2}\cos(2\omega_2 t+2\phi_2)+\cos[(\omega_1+\omega_2)t+(\phi_1+\phi_2)]+\cos[(\omega_1-\omega_2)t+(\phi_1$$

Since the PD's response cutoff frequency is much lower than the laser frequencies, only the difference frequency component remains after beating:

$$\omega_{\text{beat}} = \omega_1 - \omega_2$$

The PD output intensity, representing the generated millimeter-wave signal strength, simplifies to:

$$I_{\text{mmWave}}(t) \propto \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]$$

3. Experimental Results and Analysis

As shown in Table 1 , by loading different pixel spacings (3 pixels to 20 pixels) on the Opto-DMD surface, the millimeter-wave generation device can produce single-longitudinal-mode dual-wavelength lasers with varying wavelength spacings (0.165nm to 1.1nm), ultimately outputting millimeter-waves of different frequencies (17.23GHz to 137.36GHz).

Table 1. Correspondence Between Pixel Spacing, Dual-Wavelength Spacing, and Millimeter-Wave Frequency

Opto-DMD Pixel Spacing (pixel)	Dual-Wavelength Spacing (nm)	Millimeter-Wave Frequency (GHz)
3	0.165	17.23
4	0.220	27.47
...	...	...
20	1.100	137.36

Due to the cutoff frequency limitations of the PD and ESA (30GHz), only 17.23GHz and 27.47GHz microwaves (corresponding to 3-pixel and 4-pixel wavelength spacings) were experimentally observed, as shown in Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper]. However, the experimental apparatus is capable of generating high-frequency millimeter-waves up to 137.36GHz.

4. Millimeter-Wave Advantages and Disadvantages

4.1 Millimeter-Wave Advantages

The advantages of millimeter-wave technology can be summarized in three main aspects: abundant spectrum resources, ultra-low latency, and strong beamforming capability.

4.1.1 Abundant Spectrum Resources According to Shannon' s theorem, channel bandwidth directly determines the upper limit of communication capacity and data transmission rate. Currently, widely deployed sub-6GHz 5G systems in China can only utilize a maximum bandwidth of 100MHz. In contrast, millimeter-wave offers substantially richer spectrum resources. For instance, China' s approved 5G millimeter-wave trial bands of 24.75GHz–27.5GHz and 37GHz–42.5GHz provide 2.75GHz and 5.5GHz of available spectrum, respectively, enabling operators to construct systems with up to 800MHz bandwidth. In field tests, 5G millimeter-wave (800MHz bandwidth) has achieved cell downlink peak rates of approximately 10Gbit/s [6].

4.1.2 Ultra-Low Latency 5G NR supports multiple subcarrier spacing configurations (15kHz, 30kHz, 60kHz, 120kHz, and 240kHz), where larger subcarrier spacing corresponds to shorter slot duration. With 15kHz subcarrier spacing, the slot length is 1ms; with 240kHz spacing, it reduces to 0.0625ms. Shorter slots mean lower physical-layer latency in mobile networks. While sub-6GHz currently supports 15kHz/30kHz subcarrier spacing (corresponding to 1ms/0.5ms slots), 5G millimeter-wave bands can support 120kHz subcarrier spacing (0.125ms slot duration), demonstrating clear latency advantages.

4.1.3 Strong Beamforming Capability Antenna size is inversely proportional to frequency—higher frequencies enable smaller antennas. A 700MHz antenna measures 0.11 meters (quarter-wavelength), while a 24.75GHz antenna is only 3 millimeters, allowing integration of far more antenna elements in the same physical space to facilitate multi-stream spatial division. In the 5G era, massive MIMO arrays are essential for beamforming. Beamforming capability is proportional to the number of antenna elements: more elements produce narrower beams that concentrate energy more effectively, suppress interference, improve coverage, and enhance overall beamforming performance.

4.2 Millimeter-Wave Disadvantages

Higher-frequency electromagnetic signals experience greater free-space path loss, penetration loss, and reduced diffraction capability. The high frequency bands of millimeter-wave result in limited coverage distance, weak obstacle penetration, and susceptibility to environmental factors such as atmospheric absorption and rain fade—primary reasons for millimeter-wave’ s slow development in mobile communications.

5. Broadcasting and Television 5G Millimeter-Wave Deployment Scenario Recommendations

Despite limited coverage distance, millimeter-wave’ s ultra-large bandwidth, ultra-low latency, and ultra-high capacity will usher in a new phase of 5G development, enabling empowerment of vertical industries and typical application scenarios. This section analyzes millimeter-wave deployment scenarios for broadcasting and television 5G networks.

5.1 “700MHz + 4.9GHz + Millimeter-Wave” Low-Medium-High Frequency Hybrid Networking

From the perspectives of 5G industrial chain maturity and network deployment, broadcasting and television 5G networks in the initial construction phase will leverage the 700MHz band’ s wide coverage advantage to achieve nationwide ubiquitous coverage. Therefore, when deploying 5G millimeter-wave networks, broadcasters should effectively integrate them with low- and medium-frequency networks to implement a “700MHz + 4.9GHz + millimeter-wave” hybrid architecture. The 5G millimeter-wave component will be deployed in high-value areas, densely populated zones, and hotspot regions such as sports venues and transportation hubs.

Considering millimeter-wave propagation characteristics, 5G millimeter-wave base stations should be deployed in areas with high user density, minimal obstacles, and large open spaces.

5.2 High-Definition Video Backhaul Application Scenarios

High-definition video backhaul applications (such as free-viewpoint/multi-view sports event broadcasting, 8K video backhaul, and 360-degree panoramic highframe-rate video transmission) inevitably face large uplink bandwidth demands. The ultra-high uplink rate and ultra-low latency advantages of 5G millimeter-wave make it suitable as a wireless backhaul link, effectively satisfying high-definition video backhaul requirements for uplink rate and latency, thereby providing audiences with diverse viewing experiences.

For open high-definition video backhaul scenarios, 5G millimeter-wave base station deployment must also consider environmental weather factors (rain, snow, haze, etc.) that affect millimeter-wave propagation.

5.3 2B Industry Applications

The technical advantages of 5G millimeter-wave—ultra-large bandwidth, ultra-high rate, and ultra-low latency—can effectively expand broadcasting and television 5G millimeter-wave applications in vertical industries such as manufacturing, public cultural service construction, and social management capability enhancement. Broadcasting and television 5G should adhere to a differentiated development strategy, fully leveraging the platform and network advantages of radio and television broadcasting and network video to explore new applications of 5G millimeter-wave in vertical industries.

6. Conclusion

Compared with other optical millimeter-wave generation devices, the proposed Opto-DMD-based device offers simple operation without requiring physical movement of any modules. Tunable optical millimeter-wave signals can be generated through software control of the Opto-DMD, demonstrating significant application potential in 5G and other optical communication fields. However, the current experimental apparatus has a large volume, which is inconvenient for practical deployment. Integrating the bulk optics portion of the device represents a future research direction.

The year 2021 marked accelerated 5G technology adoption, with millimeter-wave being crucial for 5G development. Building upon the rapid development of China' s domestic sub-6GHz 5G industrial chain and increasing 5G penetration, domestic operators are actively exploring millimeter-wave application scenarios to further promote millimeter-wave technology and industrial maturation. 5G commercial applications will gradually shift from sub-6GHz-dominant deployments to a parallel "sub-6GHz + millimeter-wave" model, driving 5G toward ultra-high rates and ultra-low latency to deliver users an ultimate 5G experience.

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Note: Figure translations are in progress. See original paper for figures.