An Antenna-Integrated Photonic Millimeter-Wave Transmitter

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Abstract – In this paper, a small-scale antenna-integrated photonic millimeter-wave transmitter based upon a traveling-wave p-i-n structure is presented, comprising a transit time optimized layer structure. In conjunction with the applied planar log-periodic toothed antenna structure, we demonstrate 30-325GHz operation.

Introduction – Photonic millimeter-wave (mm-wave) generation is of great importance for many emerging markets as it allows extremely compact size, wideband tunability as well as broadband modulation capabilities and further enables the utilization of optical fibers as a low-loss mm-wave transport medium. Applications comprise broadband mm-wave transmitters for communication (e.g. within the V-, E- and F-band), mm-wave radar, mm-wave synthesizers, imaging and radio astronomy [1]-[4].

A straightforward way to generate a high-frequency mm-wave signal within the optical domain is to apply light from a dual-wavelength laser source to a photodetector converting the optical signal into an mm-wave which is further radiated via a broadband antenna. For communication purposes the generated mm-wave signal may further be modulated by a broadband data signal. However, realizing such a photonic mm-wave transmitter by using discrete components may cause high costs due to several bulky mm-wave components like coaxial cables or rectangular waveguides to connect the mm-wave photodetector with the antenna, further on mm-wave transitions and connectors leading to power losses, increased module size and higher costs. Therefore an integrated solution would be beneficiary in terms of costs and size if detector and antenna are integrated to one single chip [5].

Fig. 1 shows the operation principle of such an antenna-integrated photodetector. Light is coupled by a single mode fiber (SMF) to a passive optical waveguide (POW) which further transports the optical signal to a high-frequency photodetector operating within the mm-wave range. After detection, the converted electrical signal is coupled to an electrical waveguide, further to the feeding point of a planar antenna and transmitted. Due to the large difference in the dielectric constant between air and semiconductor, the generated mm-wave is mainly radiated through the substrate. For efficient beam-forming and coupling to free-space, an additional quasi-optics is necessary which was already reported in [6].

Photodetector Operation Principle – The developed layer structure is schematically shown in Fig. 2. Our approach comprises a traveling-wave p-i-n structure with a transit time optimized layer structure. Regarding the layer structure, the amount of slow photo-generated carriers (holes) is significantly reduced which would otherwise
contribute to the photocurrent and therefore degrade the RF-performance.

Ti/Pt/Au
Ge/Pt/AuGe/Pt/Au

lower cladding:
compensated InP:Fe-substrate

contact layer:
p+-InGaAs:Zn

drift region:
n.i.d.-InP

drift region/spacer layers:
n.i.d.-InGaAsP

intrinsic region/absorber:
n.i.d.-InGaAs

p-doped absorber:
p-InGaAs:Zn

diffusion blocker 2:
p-InGaAsP:Zn

diffusion blocker 1:
p-InGaAsP:Zn

passive waveguide core:
n.i.d.-InGaAsP

n-doped layer/passive waveguide core:
n+-InGaAsP:Si

upper cladding:
p+-InP:Zn

Fig. 2. Schematic cross section (middle) of the developed traveling-wave photodetector, enlarged active section (left hand) and 3-dimensional model (right hand).

In detail, the main improvements are a partially p-doped absorbing layer on the one side and a partially non-absorbing i-layer on the other side. A structure based on this principle, in conjunction with a thin absorber in the drift layer is expected to deliver higher photocurrent without compromising frequency response [7],[8]. Another key benefit is the applied traveling wave principle, which differs from a lumped element in a non-RC time limited response exhibiting superior high-frequency performances. This was already demonstrated e.g. in [9]-[12].

The layer structure has been successfully grown in metal organic vapor phase epitaxy. Images recorded by transmission electron microscopy show good agreement between thicknesses of designed and fabricated epitactic layers whereas analysis by x-ray diffraction shows a maximum lattice mismatching of only 0.5%.

The schematic cross section describing the specific layer functions is further shown in Fig. 2. The dielectric ridge loaded optical waveguide consists of a 50nm p-doped and additional 50nm InGaAs absorber. The drift region consisting of three InGaAsP spacer layers and the InP layer is located below the intrinsic absorber. The thickness of the non-absorbing InP drift layer is 220nm.

Beneath the drift region, two InGaAsP layers, n-doped and non-doped, form the passive optical waveguide core. Photoluminescence wavelength for non-absorbent core was determined to be 1.21μm at room temperature which means that the photomixers can be operated not only at 1.55μm but also at 1.3μm. The whole structure is grown on compensated InP substrate.

Antenna-Integrated Photodetector – Fig. 3 shows the schematics of the developed mm-wave transmitter. An applied photonic mm-wave signal using a lensed SMF is coupled to the POW, transported to the broadband photodetector and o/e-converted. After o/e-conversion, the electrical signal is coupled to a microstrip circuitry and further fed to the center of the planar log-periodic toothed antenna (LPTA).

A well-suited design was applied for the optical waveguide for achieving high coupling efficiencies. In that regard, BPM CAD simulations were carried out to calculate the overall optical coupling efficiency from a lensed SMF to the active photomixer section, i.e. lensed SMF to POW and POW to active photomixer section. It was found, that the maximum efficiency is as high as 56% if a proper geometrical design is applied.

In Fig. 4, the realized antenna-integrated photomixer is illustrated, comprising of a 2x2mm² log-periodic antenna and an approx. 1mm POW for optical feed, expending from the front surface to the active photomixer section. The photomixer, exhibiting a 70μm microstrip feed line between the active photomixer section and the antenna center, is positioned close to antenna center for low electrical losses between photomixer output and antenna feeding point.

The antenna-integrated photomixers are fabricated using conventional photolithography, wet chemical etching and metal evaporation. Lift-off technique is employed to realize the metal contacts. Electrical passivation at the interface between the active photomixer section and the coplanar output and antenna feeding point via microstrip circuitry, respectively, is implemented by a pure baked-out polyimide bridge to prevent broken microstrip feed
lines lying above the passivation. The devices are thinned down to 125μm.

Fig. 4. Photographs of the developed component. Top view of the fabricated antenna-integrated photomixer (left hand) and close up view of the center of the planar log-periodic toothed antenna with microstrip circuitry, active photomixer section and passive optical waveguide (right hand).

Packaging & Characterization – For characterizing the developed antenna-integrated photomixer, we have constructed a photonic transmitter package comprising techniques for low mm-wave loss and an efficient antenna beam generation, which was already shown in [6]. We have packaged two devices to complete modules which are shown in Fig. 5. The package consists of two DC pins to allow biasing of the antenna-integrated photodetectors, a single mode fiber with FC/APC connector and a quasi-optics (i.e. a high-resistive silicon lens) for efficient mm-wave transmission.

Fig. 5. Top view of a packaged, antenna-integrated photomixer (left hand) and side view (right hand) showing the quasi-optics for efficient radiation pattern generation.

We have characterized the modules using a set of power detectors with rectangular waveguide input and attached horn antenna (i.e. WR22 to WR03) to cover a frequency range of 30-325GHz. The measured frequency responses are shown in Fig. 6. As can be seen, both detectors exhibit a very similar response behavior with a power difference of approx. 2dB indicating a good reproducibility of the processed devices. The response exhibits a very smooth behavior with a total roll-off of about 25dB except a fall-off within 60GHz. This is attributed to an insufficient antenna size for lower-frequency operation (i.e. below 75GHz). Improved antenna designs are currently under work.

Conclusion – In this paper, we have presented an antenna-integrated photonic mm-wave transmitter based upon a traveling-wave p-i-n diode with an advanced partially p-doped and partially non-absorbing layer structure. The advanced photodetector layer structure in conjunction with the applied broadband LPTA-structure as well as applied optical and electrical coupling techniques allow a broadband operation. After packaging to modules, operation within 30-325GHz was demonstrated for two antenna-integrated photomixers.

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References


