A Linear Cascade Near-Ballistic Uni-Traveling-Carrier Photodiodes with Extremely High Saturation-Current Bandwidth Product (6825mA-GHz, 75mA/91GHz) under a 50Ω Load

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Abstract: We demonstrate linear cascade near-ballistic uni-traveling-carrier photodiodes. Compared with control (a single device), this novel structure exhibits significant improvement in bandwidth-efficiency and saturation-current-bandwidth products. Record-high saturation-current-bandwidth product (>6825mA-GHz, 91GHz) under 50Ω loads can be achieved.

OCIS codes: (230.5170) Photodiodes, (230.5160) Photodetectors

I. Introduction

Saturation current-bandwidth product (SCBP) is a key parameter to evaluate the performance of high-power photodiode (PD) for the application of radio-over-fiber (ROF) communication system, especially when the carrier frequency is up to over 100GHz. By increasing the saturation current of PD, we can boost the injected optical power and further increase the maximum available MMW power from PD and the burden imposed on the MMW power amplifier can thus be released [1]. The key point to pursuit the ultimate high SCBP of PD is to downscale the photo-absorption active area also its depletion layer thickness. A thinner depletion layer thickness indicates a larger junction capacitance, a shorter carrier transit time, and a higher saturation current performance of PD [2]. The downscaling of device active area is thus necessary to sustain a low junction capacitance and achieve very-high speed performance. However, device-heating and high parasitic resistance should be problems, which seriously limit the saturation current for the PD with such a small active area (~10μm^2). By reducing the load resistance of miniaturized size of PD to 25 or 12.5Ω [3], ultra-high speed performance (~300GHz) can be achieved. However, the values of photo-generated RF power will decrease 3dB and 6dB for 25 and 12.5Ω loads, respectively. Downscaling the active area of uni-traveling carrier (UTC-PD) to 13μm^2, 170GHz optical-to-electrical (O-E) 3-dB bandwidth with around 14mA maximum output photocurrent (SCBP: 2380mA-GHz) has been demonstrated under a 25Ω load [2,4]. One attractive way to further improve the SCBP of PDs is the use of the distributed (traveling-wave, TW) structure. By uniforming the distribution of photocurrent in the enlarged photo-absorption volume of TW structure, which is composed of several miniaturized PDs with a low-loss electrical transmission line, extremely high SCBPs has been demonstrated by use of UTC-PDs [5,6] (1938mA-GHz, 17GHz, 114mA [6]) and p-i-n PDs (1760mA-GHz, 80GHz, 22mA) [7]. However, in TW structure, the phase of injected optical wave must be carefully matched with that of photo-generated electrical wave, and complex design of electrical/optical (EO) structure is necessary [5-7]. In addition, the effective load resistance in TW structure is around 25 Ω due to that the 50 Ω dummy load in the input-end is necessary to absorb the reflected electrical wave [5-7]. In this paper, we demonstrated a novel structure of PD: linear cascade PD, to further enlarge the active photo-absorption volume and improve SCBP also bandwidth-responsivity product (BRP) performances of PDs under a standard (50Ω) load resistance. In such all-lumped structure the complex design of EO structure is not necessary. By integrating the high-power NBUTC-PDs [8] with such novel structure with a very-large total active area (578μm^2), 1.7 and 3.4 times higher BRP and SCBP have been achieved as compared to the control with a single NBUTC-PD and a 289μm^2 active area. Record high SCBP (>6825mA-GHz, 91GHz/>75mA) by use of our linear cascade NBUTC-PDs can be achieved.

II. Device Structure

Figure 1 (a) to (d) shows the top-view of single NBUTC-PD, linear cascade two-element NBUTC-PDs, flip-chip bonded single NBUTC-PD, and linear cascade two-element NBUTC-PDs, respectively. The detail epi-layer and geometric structures of back-side illuminated flip-chip bonding NBUTC-PDs is similar with that given in our previous work [8] except for the load resistance. In this work, we use a single-ended co-planar waveguides (CPWs) and the load resistance is 50 Ω instead of 25 Ω in our previous work [8]. The flip-chip bonding pedestal is composed of an AlN substrate, which has a high thermal conductivity and low dielectric loss, and three metal stripes on it serve as the CPWs. The inset to Figure 1 shows the conceptual diagram of cascade PDs during operation. As can be seen, this structure is consisted of serial connection of several PDs (two in our case), which should result in that the values of total junction capacitance reduce according to the number of PDs for serial connections. Although serial connection also accompanies the increase of parasitic resistances of PDs, which may degrade the advantage of capacitance reduction, the total resistance should not linearly increase with the number of cascade units

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due to the existence of 50Ω load resistance. An improved RC-limited bandwidth of cascade array can thus be expected [9]. In this work, two NBTUC-PDs are adopted in the linear cascade structure for easy optical alignment. During operation, the illuminated optical power on such two devices must be kept the same to get the maximized responsivity. Contrary to the structure of TWPDs, the optical phase in our demonstrated all-lumped structure is not necessary to fine tune to get the maximum flatten O-E frequency responses [6]. This advantage should greatly benefit to reduce the package cost of devices for practical use.

III.Measurement Result:

The measured DC responsivity of control device is around 0.12A/W, which is around twice higher than that of cascade structure due to that the optical power must be equally divided onto two PDs in cascade structure. The optical-to-electrical (O-E) frequency responses and photo-generated RF power of devices were measured with a two-laser heterodyne beating system with three different MMW power sensor heads for a range from DC to 50GHz, V-band (50-75GHz), and W-band (75-110GHz). The traces with open and close squares in Figure 2 show the measured O-E frequency responses of control and cascade devices under -3V and -6V reverse bias voltages, respectively. As can be seen, the measured 3-dB bandwidth of cascade structure even with a large total active area (578μm^2) can be as high as 91GHz and is around three times higher than that of single control (91 vs. 27GHz) due to the improvement in its RC-limited bandwidth. Based on such measurement result, we can thus conclude that by use of cascade structure, we can get around 1.7 times higher BRP than that of single control. Figure 3 shows the measured photo-generated RF power of cascade devices and single control versus the photocurrent under -10V and -5V fixed reverse bias voltages, respectively. The operating frequency is fixed at 91 and 27 GHz for cascade and single device, respectively. As can be seen, the measured saturation current of both devices is the same and over 75mA, which is limited by the thermal failure. Although the required bias voltage of cascade structure is around twice higher than that of single device, the measured saturation current of both structures is exactly the same due to that the total active area of cascade structure for heat-sinking is also twice larger than that of single control (289 vs. 578μm^2). Compared with the measured SCBP under room temperature operation of single control, our demonstrated cascade structure exhibits around 3.4 times higher SCBP, which is as high as over 6825mA-GHz (91GHz, >75mA) under 50Ω load. Such value is superior to all of those reported for high-performance InP based PDs with 50 or 25Ω loads, such as, parallel-fed traveling wave PDs (17GHz, 114mA, 1938mA-GHz [6], 80GHz, 22mA, 1760mA-GHz [7]), UTC-PDs (170GHz, >14mA, >2380mA-GHz [5], 50GHz, 50mA, 2500mA-GHz [10]), and single NBUTC-PD (>110GHz, 37mA, >4070mA-GHz [8], under 25Ω load) under the similar heterodyne-beating CW-measurement.

IV.Summary:

In conclusion, we have demonstrated a novel structure for further improving the SCBP and BRP performances of high-speed PDs: linear cascade PDs, which is flip-chip bonding on the AlN substrate for good heat-sinking. Due to the great improvement in RC-limited bandwidth of such all-lumped structure, the complex design of EO structure in TWPD can be eliminated. A record-high SCBP (91GHz, >75mA, >6825mA-GHz) ever reported for InP based high-speed PDs has been demonstrated.

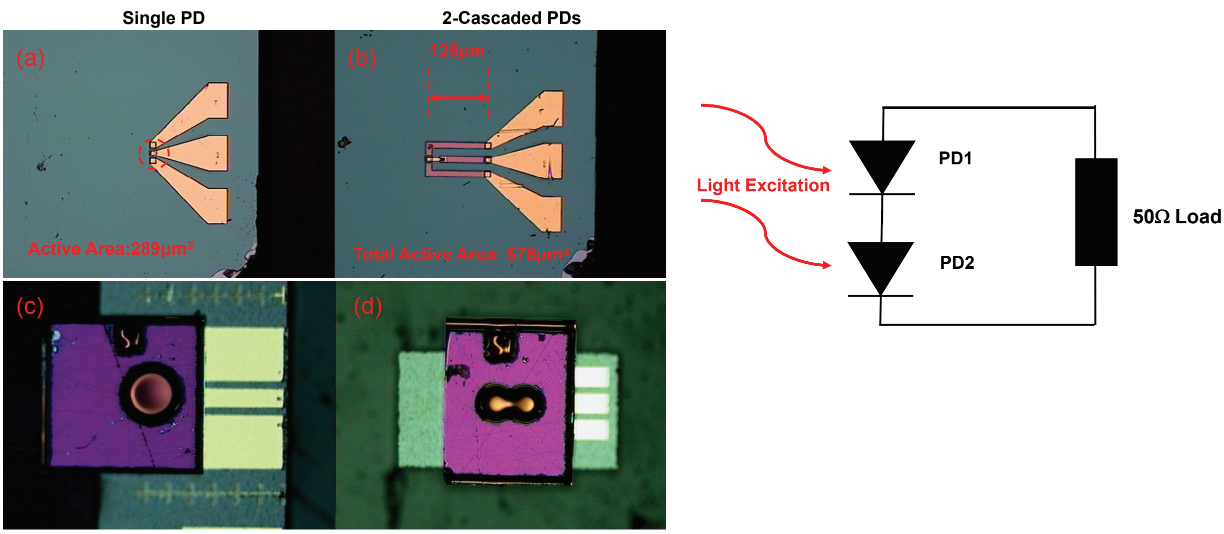

Figure 1. The top-view of single control NBUTC-PD (a), two-element linear cascade NBUTC-PDs (b), flip-chip bonded single control (c), and liner cascade NBUTC-PDs (d). The inset shows the conceptual diagram of 2-cascade PDs during operation.

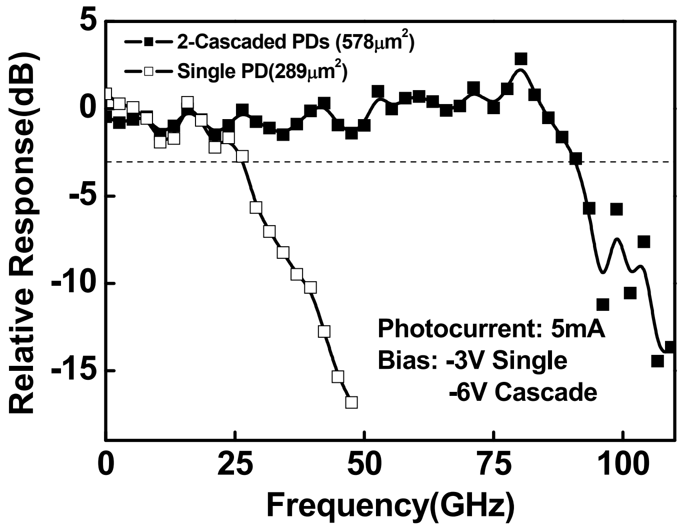

Figure 2. The measured optical-to-electrical (O-E) frequency responses of single control and cascade structures.

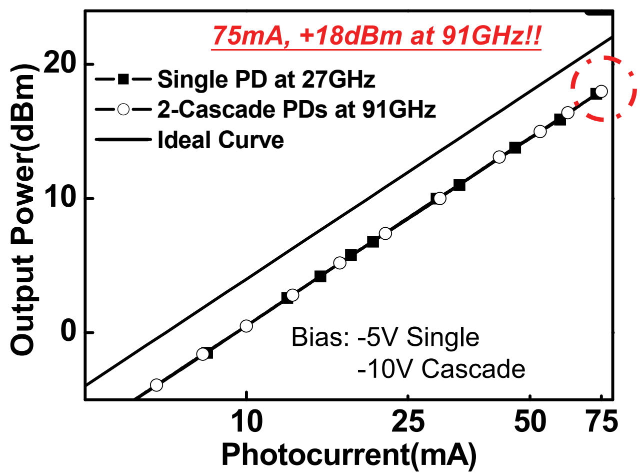

Figure 3. The maximum output RF power of single control and cascade structure versus output photocurrent for an operating frequency fixed at 27 and 91GHz, respectively.

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