

A 60-GHz LTCC SiP with Low-Power CMOS OOK Modulator and Demodulator

Chul Woo Byeon*, Jae Jin Lee**, Hong Yi Kim*, In Sang Song*, Seong Jun Cho*, Ki Chan Eun*, Chaejun Lee*, and Chul Soon Park*

Abstract—In this paper, a 60 GHz LTCC SiP with low-power CMOS OOK modulator and demodulator is presented. The 60 GHz modulator is designed in a 90-nm CMOS process. The modulator uses a current reuse technique and only consumes 14.4-mW of DC power in the on-state. The measured data rate is up to 2 Gb/s. The 60 GHz OOK demodulator is designed in a 130nm CMOS process. The demodulator consists of a gain boosting detector and a baseband amplifier, and it recovers up to 5 Gb/s while consuming low DC power of 14.7 mW. The fabricated 60 GHz modulator and demodulator are fully integrated in an LTCC SiP with 1 by 2 patch antenna. With the LTCC SiP, 648 Mb/s wireless video transmission was successfully demonstrated at wireless distance of 20-cm.

Index Terms—60 GHz, mm-wave, system-in-package (SiP), low temperature co-fired ceramic (LTCC), on-off keying (OOK), CMOS

I. INTRODUCTION

Recently, demand has been increasing for a millimeter-wave (mm-wave) frequency band due to the congestion and bandwidth limitation associated with low-gigahertz frequency bands. A multi-gigabit data rate can easily be attained with a simple modulation scheme using the 60 GHz unlicensed band.

With handheld devices containing more storage and powerful than ever before, at present most people normally carry some type of mobile device. A low power system is a key issue for these applications, as they are typically battery-operated. However, CMOS based 60 GHz systems [1-3] consume a considerable amount of DC power due to their level of system complexity. Therefore they cannot easily be applied in mobile devices.

The self-heterodyne architecture based on on-off keying (OOK) modulation is a promising solution for mobile devices owing to its low-power characteristics and simplicity [4]. A CMOS-based mm-wave OOK modulator and demodulator [5-7] has already shown considerable promise for future multi-gigabits short-range mobile communications.

Section II shows the architecture of the OOK transceiver system introduced here. Section III shows the CMOS circuit description. Section IV describes the 60 GHz LTCC SiP, and sections V and VI respectively show the experimental results and present the conclusion.

II. SYSTEM ARCHITECTURE

Fig. 1(a) shows OOK transmitter based on the self-heterodyne scheme [8]. In contrast to a typical RF transmitter, the OOK transmitter consists of a signal generator, an up-mixer, and a power amplifier (PA). It does not reject a local carrier in a transmitted signal. In other words, it sends the local carrier signal and RF data signal at the same time. The self-heterodyne receiver receives the signal, including the data and local carrier signal, and amplifies them by using a low noise amplifier.

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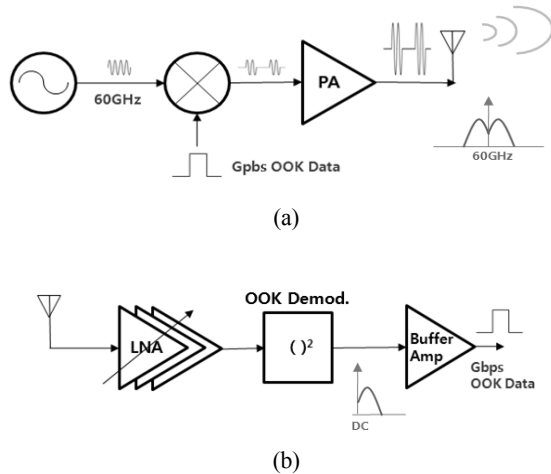


Fig. 1. Conventional OOK. (a) Transmitter and (b) Receiver based on the self-heterodyne structure.

The amplified signal is sent to a square-law detector which detects and recovers the data by mixing the RF data and the received local carrier signal. Thus, the data recovered at the output of the detector are amplified by the buffer amplifier. The self-heterodyne structure is said to be a non-coherent detection technique because the receiver uses the received 60 GHz local carrier coming from the transmitter to restore the data. In other words, the transmitter and receiver share the local carrier signal. Thus, it does not require a PLL at the transmitter and receiver to lock the phase. Specifically, receiver has no local signal generator, which helps to simplify the architecture of the transceiver system and finally to reduce the total DC power dissipation of the system.

With the self-heterodyne structure, we can reduce the DC power dissipation on account of its simplicity; however, this structure has two main limitations. First, the PA still requires high DC power dissipation for high output power to cover the high path loss at 60 GHz. Second, the receiver requires many amplifiers before the square-law detector to boost a low receiver input signal by the sensitivity of the detector. In a general, in an OOK transmitter, the PA consumes the largest amount of DC power in the system, and it is always on. In particular, the power-added efficiency (PAE) of a millimeter-wave PA is only about 7-12% at a 1-dB compression point. This low PAE is the main obstacle when seeking to apply a millimeter-wave system to battery-operated mobile devices. Thus, the best way to increase the power efficiency of a transmitter is to reduce the inefficient DC

power consumption of the PA. Moreover, conventional mm-wave OOK detectors, such as square-law detectors, require a high level of input power to ensure a high conversion gain. Because the conversion loss of the detector decreases as the input power level increases, the receiver requires many amplifiers with a high gain to give sufficient input power to the detector. This increases the total DC power consumption of the receiver. The improved conversion gain of the demodulator with low input power helps to reduce the total DC power dissipation of the self-heterodyne receiver.

To solve the drawbacks of the self-heterodyne structure, we propose a new architecture involving an OOK transceiver structure based on a self-heterodyne architecture. The proposed OOK transmitter consists of a 60 GHz local signal generator and a 60 GHz OOK modulator which can replace both the PA and up-conversion mixer, as shown in Fig. 2(a). The modulator is only turned on when the OOK digital signal is in the “on-state,” while during the “off-state” of the OOK digital signal, the OOK modulator is turned off. Because there is no DC power dissipation in the off state, we can reduce the amount of DC power used by up to 50% at the PA. An OOK receiver is very similar to the conventional OOK receiver, as shown in Fig. 1(b). The proposed demodulator adopts a gain-boosting technique to improve the data rate and the conversion gain [6]. With the gain-boosting technique, the improved conversion gain helps to reduce the burden of the DC power dissipation of the

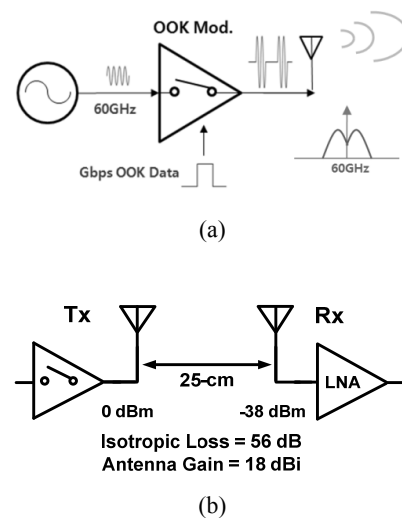


Fig. 2. (a) Proposed OOK transmitter structure and (b) Link budget.

amplifiers.

The link budget can be described as shown in Fig. 2(b). The modulator provides output power of about 0 dBm, which leads to -38 dBm input power at the receiver front-end after 25-cm radiation distance.

The 60 GHz OOK modulator and demodulator are the main blocks of the 60 GHz OOK transceiver structure based on a self-heterodyne scheme. At this point, it is necessary to improve the performance of the 60 GHz OOK modulator and demodulator considering the low DC power dissipation requirement of mobile applications.

III. CIRCUIT DESCRIPTION

1. 60 GHz CMOS OOK Modulator

The main requirements of an OOK modulator are a high on/off isolation, a high gain in the on-state, low DC power consumption, and processing at a high data rate. Additionally, as the 60 GHz OOK modulator replaces the PA, high output power becomes another key factor in the proposed transmitter. A switching amplifier mode is adopted in a 60 GHz OOK modulator for high gain and high data processing rate despite the continuing problem of low on/off isolation. Fig. 3 shows a schematic of the proposed 60 GHz OOK modulator. The total width of both M_1 and M_2 is $42 \mu\text{m}$ which guarantees that OP1dB is higher than 1 dBm; its current density is $200 \mu\text{A}/\mu\text{m}$ to maximize the f_{max} value of the transistor [4]. A current reuse technique is adopted between two cascaded common source (CS) amplifiers (M_1 and M_2) to reduce DC current consumption [9, 10]. It is implemented using micro-strip (MS) lines (MS_4 , MS_5 , and MS_7) as well as a coupling capacitor C_2 and a bypass capacitor C_3 , which connect the first CS amplifier (M_1) to the second CS amplifier (M_2). The 60 GHz signal amplified by M_1 passes through the inter-stage matching network including MS_5 , MS_7 , and C_2 , and then enters the gate of M_2 . At the same time, MS_4 and C_3 create high impedance at 60 GHz to block the amplified 60 GHz signal by M_1 entering the source of M_2 . All transmission lines in the circuit design are formed using an MS line that consists of a signal line and a ground plane located on the top metal (metal 9) and bottom metal (metal 1), respectively. The signal-to-ground spacing is $6.145 \mu\text{m}$. All metal layers are copper, while the insulator layer is SiO_2 with an effective

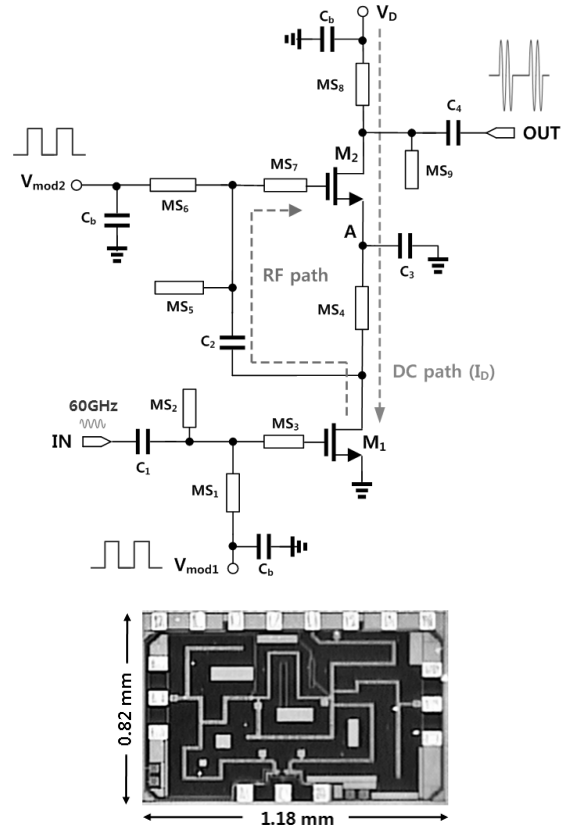


Fig. 3. Schematic of the proposed 60 GHz OOK modulator and a chip photograph.

dielectric constant of 3.7.

OOK modulators based on an amplifier modulate the signal by controlling only the gate bias of the common gate stage in a cascode structure [11-13]. This scheme causes change in the drain-source voltage of M_1 (V_{ds}), which finally modulates the 60 GHz signal only at M_1 . However, this has led to problems such as 60 GHz signal leakage in the off-state, which results in low on/off isolation, and the necessity of a large control signal given the difficulty of turning off M_1 perfectly by varying V_{ds} . In the proposed 60 GHz OOK modulator, the baseband signal enters the gate biases (V_{mod1} and V_{mod2}) of M_1 and M_2 at the same time. This is termed dual-modulation technique, as shown in Fig. 3. Even if the data signal (V_{mod1}) near the threshold voltage of M_1 is small, M_1 , acting as the current source of an amplifier, can be turned off perfectly and there is no generated 60 GHz signal at the output of M_1 with zero data. Additionally, the summation of V_{mod2} and the inverted V_{mod1} signals passing through M_2 and M_1 individually create little voltage variation of node A, similar to an AC ground.

This allows the baseband signal of $V_{\text{mod}2}$ to turn M_2 on and off, which helps M_2 refine the 60 GHz OOK modulated signal generated by M_1 once more. Therefore, M_1 and M_2 work together. These innovations allow a high level of on/off isolation of 28.4 dB and high gain of 9.9 dB at 60 GHz.

2. 60 GHz CMOS OOK Demodulator

A simplified schematic of the proposed 60 GHz OOK demodulator circuit diagram is shown in Fig. 4. All of the transistors use a minimum gate length of 0.13- μm . The demodulator consists of a detector (M1-M5) and a baseband amplifier (M6-M11). The modulated 60 GHz OOK signal is applied to the input of the detector, and M1 detects the digital information, which is the envelope of the 60 GHz modulated signal. To analyze the operation principle of the M1 transistor, we used the Taylor expansions from [14]. The simplified drain current in the Taylor expansions can be expressed as follows:

$$i_{DS} = I_{DS} + g_m v_{in}(t) + \frac{1}{2!} g_{m2} v_{in}(t)^2 + \frac{1}{3!} g_{m3} v_{in}(t)^3 + \dots, \quad (1)$$

where I_{DS} is the DC drain current, $v_{in}(t)$ is the input voltage, g_m is the transconductance, and g_{m2} , and g_{m3} are the second and third higher-order derivatives of i_{DS} with respect to $v_{in}(t)$, respectively. The desired output in equation

(1) is $0.5g_{m2}v_{in}(t)^2$. The output voltage can be simply expressed as i_{DS} multiplied by the output resistance. We assume that $v_{in}(t) = v_{in} \{ \cos(\omega_{RF}t) + a \cos((\omega_{RF} + \omega_{IF})t) \}$.

The voltage conversion gain is $0.5g_{m2}v_{in}R_O$, where R_O is the output resistance. Note also that the voltage conversion gain is proportional to the derivative of the transconductance, g_{m2} , the output resistance, and the input voltage. We should, therefore, choose a gate bias point of 0.42 V where g_{m2} is maximized for a higher conversion gain and where the parasitic capacitance is minimized for a higher data rate. Input matching of the detector was done with MS lines (L_1 - L_4).

The additional gain-boosting [15] stage using M2 and M3 is employed for higher conversion gain using extra voltage headroom. The conventional detector uses a single NMOS transistor [16]. As additional transistors of the M2 and M3 are added to the conventional detector of M1, the gain-boosting stage increases the effective transconductance from the gm of the common gate of M3 without M2 to the $(1 + A)gm$ of M2 and M3, where A is the gain from the common source of M2. Therefore, the voltage conversion gain is increased $(1 + A)gmR_{O3}$ times greater than the voltage conversion gain of a conventional NMOS detector. In this expression, R_{O3} is the output resistance at the drain of M3. By inserting a gain-boosting stage, the conversion gain is improved at the cost of the additional DC power of 0.6 mW for M2. High parasitic capacitance disturbs the high data rate, and the low source input impedance of M3 reduces the conversion gain of the detector. To avoid both the low input source impedance of M3 and the high parasitic capacitance, we chose small transistor widths of 18 μm and 20 μm for M2 and M3, respectively. With gain-boosting technique, the proposed detector has high voltage responsivity of 2434 mV/mW at 60 GHz.

M6 to M11 are used as a three-stage resistive feedback baseband amplifier; and the amplifier increases the output voltage to a specific level. Each stage simultaneously employs an NMOS and a PMOS for higher transconductance. Furthermore, the gate bias is self-biased depending on the transistor size ratio of the NMOS and PMOS whose currents are identical. The voltage gain, A_v , of each stage of the resistive feedback amplifier and the 3-dB bandwidth, ω_c , can be derived as

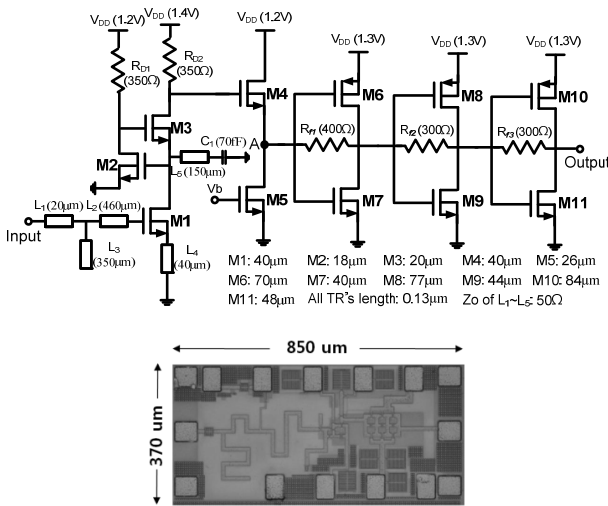


Fig. 4. Schematic of the proposed 60 GHz OOK demodulator and a chip photograph.

$$Av = \frac{v_o}{v_{in}} = \frac{-(g_{mN} + g_{mP})(R_O // R_f)}{(1 + sC_{in}(R_s // R_f))(1 + sC_{out}(R_O // R_f))} \quad (2)$$

$$\omega_c = \frac{1}{(R_s // R_f)C_{in}}, \quad (3)$$

where g_{mN} and g_{mP} are the transconductance of the NMOS and PMOS, respectively. R_f is the feedback resistance, R_s is the source resistance, R_O is the output resistance without R_f ; and C_{in} and C_{out} are the equivalent parasitic capacitance of the input and output, respectively. The three-stage resistive feedback amplifier has a simulated voltage gain of 17.3 dB and a 3-dB bandwidth of 4 GHz.

IV. 60 GHz LTCC SYSTEM-IN-PACKAGE

Multi-chip modules (MCM) have features that enable a smaller and lighter system and higher speed performance by eliminating individual packages and the resulting parasitic. MCM technology is one of the most efficient packaging technologies for high density integration. The bare chips are attached to the substrate by wire bonding or flip chip bonding. In this approach, the size of the package is determined by the size and number of the IC devices and number of input and output connections per device. MCM substrates consist of not only interconnection lines but also many embedded passive components. Therefore, by employing MCM technology, the package size will be minimized. Specifically, a compact size, high integration, and simple implementation with high performance at the mm-wave are important issues when applying a low temperature co-fired ceramic (LTCC) SiP in a mobile device.

One of the most important characteristics of LTCC technology is the capability of providing multilayer integration. LTCC technology provides a single package solution by integrating embedded passive components and attached MMICs. This strategy replaces discrete components with embedded components while adding functional components to the package, such as a filter, a balun and an antenna. It can also realize high-Q embedded passive components such as a high-Q inductor and can provide low parasitic interconnections such as flip-chip and BGA. Moreover, LTCC has a relative

permittivity of 5.8 with a 0.0035 loss tangent and conductors of silver and gold at 6.1×10^7 S/m and 4.1×10^7 S/m, respectively. They help to create low-loss millimeter-wave integration. It is possible for LTCC to use a three-dimensional interconnection and cavity process, making it is easy to integrate passive circuits in a single module with MMICs.

Fig. 5 shows the 60 GHz OOK LTCC SiP transmitter with the fabricated modulator chip in Fig. 3 and receiver modules with the demodulator chip in Fig. 4. All mm-wave inputs and outputs of the chips are connected by the bonding wires, and inductance of the bonding wires is resonated out by the matching networks between the chips and between the chip and the antenna in the LTCC. Fig. 6 shows the LTCC bonding wire matching network and the return loss. The bonding wire length is approximately 0.55 mm, and they are connected to each mm-wave input and output of the chips. To reduce the effective inductance, two parallel bonding wires are connected. Fig. 6 shows a well-matched return loss with a bonding wire length ranging from 0.5 mm to 0.6 mm.

The transmitter and receiver each have a 1 by 2 patch antenna. The antennas, fed by the bonding wires and with an inter-stage matching network, radiate through the coplanar waveguide with the ground to the embedded micro-strip line. The antenna integrated using an LTCC micro-strip structure shown in Fig. 5 has a high simulated gain of 9.8 dBi. The half-power beam width of the antenna is 30°. The sizes of the OOK-based five-layer LTCC transmitter and receiver are 21.2 mm x 11.6 mm x 0.5 mm and 25.5 mm x 10.5 mm x 0.5 mm, respectively.

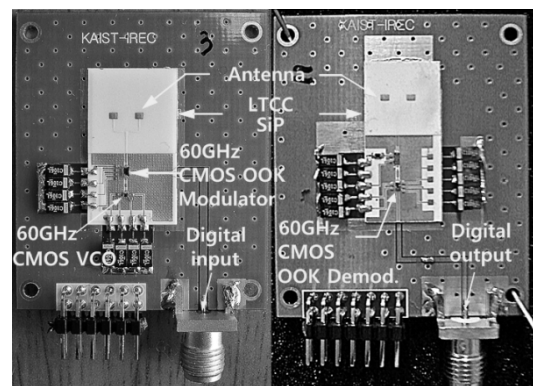


Fig. 5. 60 GHz OOK SiP modules. The transmitter is on the left and the receiver is on the right.

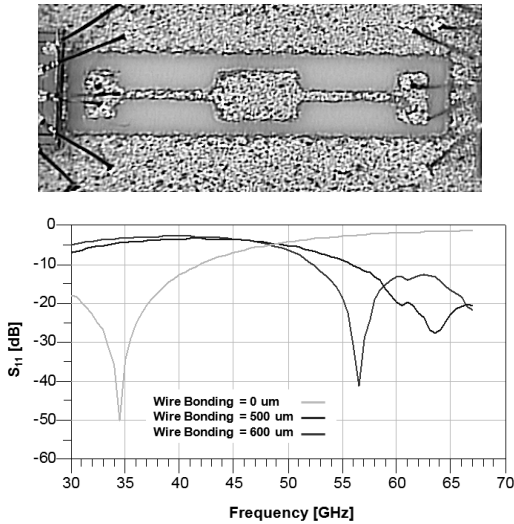


Fig. 6. LTCC bonding wire matching network and return loss with and without wire bonding.

V. EXPERIMENTAL RESULTS

The proposed modulator and demodulator were fabricated with standard 90-nm and 0.13- μm CMOS technology, and consumes 14.4 mW at on-stat and 14.7 mW, respectively. Conversion gain of the modulator and demodulator is 9.9 dB and 13.6 dB for -16 dBm input at 60 GHz, respectively. Fig. 7 shows the measured 2 Gb/s modulated '1010' data at the modulator output and the recovered 5 Gb/s 2^{31} -1 PRBS data at the demodulator output. Further modulator and demodulator measurement details are presented in [5] and [6].

Fig. 8 presents a block diagram of the 60 GHz wireless data link over 20 cm. Fig. 9 shows the demonstration picture, corresponding to Fig. 8, of the wireless video transmission using the fabricated 60 GHz OOK-based LTCC SiP transmitter and receiver modules in Fig. 5. The DSP generates serial digital data from the Audio/Visual data of a DVD player or a mobile phone,

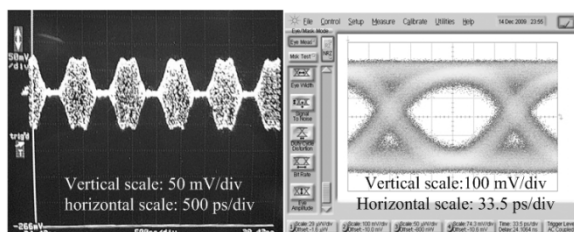


Fig. 7. Measured 2 Gb/s data at the modulator output and recovered 5 Gb/s 231-1 PRBS data at the demodulator output.

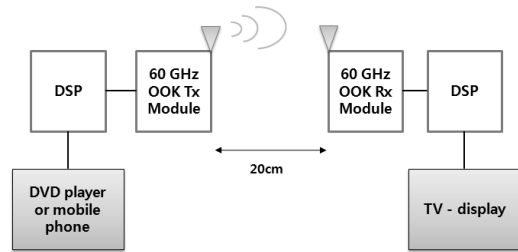


Fig. 8. Block diagram of a short range wireless data link.



Fig. 9. Demonstration of the wireless video transmission using the fabricated LTCC SiP transmitter and receiver modules.

and this serial data is applied to the 60 GHz transmitter. The 60 GHz receiver recovers the serial data from the OOK-modulated signal generated at the transmitter. Finally, the DSP after receiver converts from serial data to AV data and supplies it to the display. Using these 60 GHz LTCC SiP modules, 648 Mbps wireless video transmission was successfully demonstrated over a wireless distance of 20-cm.

VI. CONCLUSIONS

We propose a 60 GHz LTCC SiP with low-power CMOS OOK modulator and demodulator. The modulator modulates up to 2 Gb/s while consuming 14.4-mW in the on-state. The demodulator can recover modulated signals up to 5 Gb/s with 14.7 mW of DC power. The fabricated 60 GHz modulator and demodulator were successfully integrated into LTCC SiP modules. With these modules, 648 Mb/s wireless video transmission was successfully demonstrated at a 20-cm wireless distance, which shows the possibility of the low power and high data rate system with OOK modulation.

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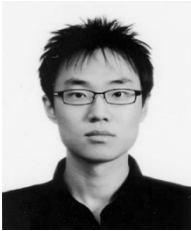
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