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Developments of high-efficiency GaN RF amplifier and pre-distortion technique for nano/small satellite downlink system

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Abstract A high-speed downlink communication system is required to meet different applications for nano/small satellites. Therefore, it is essential to implement a power- and weight-limited transmitter in such satellites. Our recent research has focused on an efficient system with the limited transmitter incorporating a powerful ground station receiver. Generally, an operation at nonlinear region provides a RF power amplifier with high energy efficiency. However, an amplitude-phase modulation, which is an efficient scheme in term of frequency band, requires high linearity. Digital pre-distortion on the transmitter is known as a powerful complementary nonlinearity of power amplifier. We are developing pre-distortion scheme for nano/small satellite transmitter. And we developed a new measurement method to evaluate the transmitter system. We will report the results of evaluation of the new transmitter engineering model. The results indicate that the new PA performances are suitable for multi-level modulation high-speed downlink system with pre-distortion such as 16-QAM system. Therefore, the power amplifier with high efficiency can be implemented.

Keyword: small satellite, satellite communication system, down link, X band, GaN-HEMT power amplifier, pre-distortion.

1. Introduction

Recently technologies of small satellites have been so matured that many earth observation missions are proposed [1]. However, it is true that nano/small satellite missions still have many limitations of satellite functions compared to large satellites. Their main limitations are down-link capabilities as well as sensing capabilities.

The purpose of this research is to develop a high-data-rate (typically over 300Mbps) communication system which can be applicable to small satellites of 50 kg class. We will demonstrate our technologies on orbit using Japanese Hodoyoshi-4 Satellite, scheduled to be launched in 2013[2, 3].

Conventional large satellites are provided with several hundred Mbps down-link system which consume high power consumption of one or more hundreds watt . A typical small satellite with 50kg, however, can generate only as small as power of around 100 W as total. This is a power constraint for a high-data-rate communication system for small satellites.

We have been developing the communication subsystem both for the flight hardware as well as the ground system, paying attention to reduce the DC power consumption and the mass of onboard instruments. In addition, we have developed a new measurement method to evaluate the transmitter system.

Section 2 describes outline of our novel high-data-rate down-link system for nano/small satellites and other conventional downlink systems. And Sec.4 shows our novel GaN HEMT X-band power amplifiers and measurement result of the engineering model. Then our approach of pre-distortion in the system is described in Sec.4. Our newly developed measurement systems for pre-distortion are described in Sec.5. The evaluation results of whole onboard transmitter system engineering model are shown in Sec.6. Sec.7 is the conclusions.

2. Transmitter system

Recent earth observations such as optical imaging and SAR imaging by satellites require higher spatial resolutions and more image data. This means that the down link data volume should be increased.

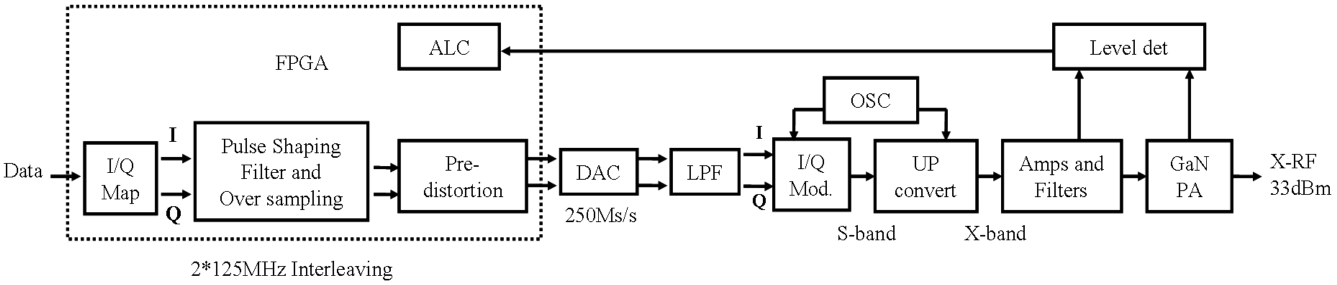


Fig.2.3 X-band transmitter system

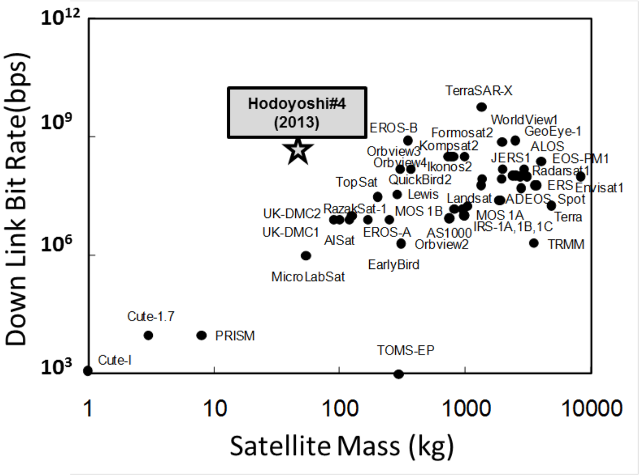


Fig.2.1 Down link bit rate vs. satellite mass for low earth orbit. ★denotes our novel technology.

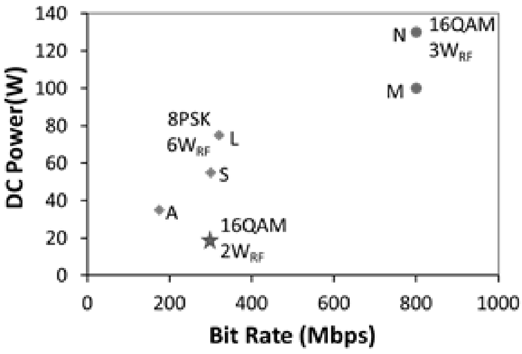


Fig.2.2 DC power consumption vs. data bit rate for onboard high-data-rate transmitter. ◆ and ● correspond to conventional transmitters with 8PSK and 16QAM, respectively. ★ denotes our novel transmitter with 16QAM. RF power levels are also indicated.

Table.2.1 System requirement

Center frequency	8.16GHz(X-band)
Band width	150 MHz
Modulation scheme	QPSK,16QAM
Mod. symbol rate	10 Msps,100 Msps
Avg. RF power	33dBm(2W)

One way to increase the down link data volume is to use data relay satellites such as TDRSS of USA and DRTS of Japan. In this scheme, a long visible time compensates its relatively low bit rate for long communication range between a geo-synchronous orbit and a low earth orbit. However, this method is expensive. Also the data relay link requires additional communication instruments and antennas for a space-space link.

Therefore, a cost-effective approach to increase the down link data volume seems to increase a data rate of downlink to an earth station which has a short visible time around 10 minutes. Fig.2.1 indicates down link data rates of low earth orbiting satellites as a function of satellite mass [4]. The figure shows that down link data rates are proportional roughly to linear or square of satellite mass. This is because in general a down link with a high data rate requires high power consumption and large mass.

Conventional communication systems of large satellites have capability of hundreds Mbps through 1Gbps and in most cases they utilize X band (8025-8400MHz) for earth observation. The maximum bandwidth is 375MHz and in most cases a convolution coding with r=1/2 is applied. Therefore multi phase-shift-keying and amplitude-phase modulation are necessary to achieve higher bit rates than 300 Mbps.

These modulations, however, are sensitive to nonlinear distortion of RF power amplifiers. RF power amplifiers have to operate in linear region, which causes reduction of power efficiency. Also they require digital processing circuits with several hundred MHz clock. Fig.2.2 shows power consumptions as a function of data bit rate for onboard X-band transmitters with high data rates. Their power consumptions increase as the data bit rates increase with bandwidth-effective modulations.

As sum of them, the conventional high-data-rate communication system of large satellite requires 100W or 200W as a whole for DC power consumption.

Since a ground station communicates with various satellites, a ground demodulator is required to have a clear interface with satellite. In most cases, conventional high-data-rate ground demodulators have been developed separately from developments of onboard transmitters. Manufacturers of ground station systems including parabolic antennas have also developed ground receivers. These situations have led to developer of ground demodulators to pay little attention to compensate or adapt imperfectness of onboard transmitter such as nonlinearity, an error angle of I/Q axes and frequency dependences.

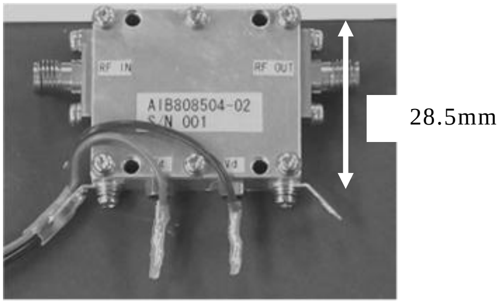
Recently novel technical improvements of wireless communications have been emerged. It is desired to apply the “adaptive technology” to the high-data- rate demodulator for earth observation satellites.

As a result, the block diagram of our onboard system is now roughly shown in Fig.2.1.

3. GaN HEMT X-band power amplifier

Table.4.1 GaN-HEMT AB power amplifier

Drain voltage	28V
Drain current(no RF)	125mA
Class	AB
Operating frequency	8.15GHz-8.35GHz
Avg. output power	34dBm
Size	33.6mm×28.5mm×9mm

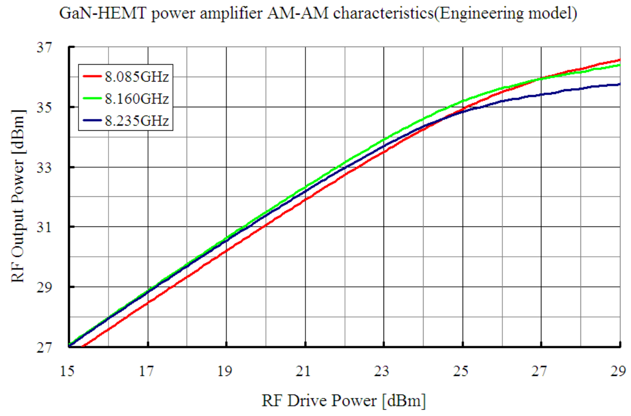


F.g.3.1 Photograph of GaN-HEMT class-AB power amplifier engineering model(EM)

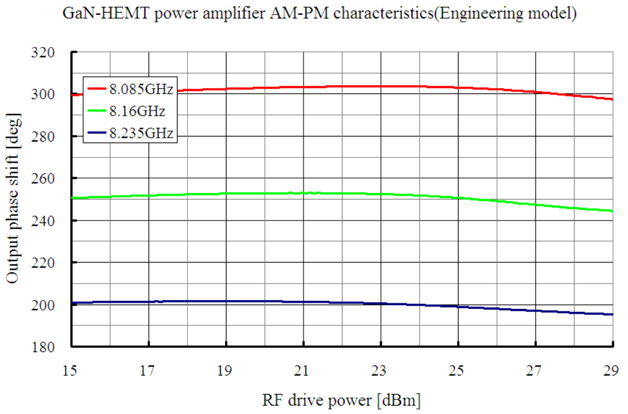
Our novel power amplifier is optimized for nano/small satellites. That is smaller PCB and package design, high PAE (Power Additional efficiency) and optimized for pre-distortion technique. And measurement results of an engineering model are shown below.

The symbol rate we use is 100Msps and the effective frequency bandwidth is about 150MHz (roll off coefficient is 0.5), which is just 1.8% of the carrier frequency 8.16 GHz. The frequency dependences of AM-AM characteristics of Fig.3.2 are by less than 1dB while the nonlinearities are by 2-3 dB in terms of compression power level. And an AM-PM characteristic of Fig.3.3 shows that phase shift is under 5degrees over the entire frequency range we use. This value is about 1/3 to 1/2 for the value of a conventional GaAs FET amplifier. As sum of them, this power amplifier con be used in lower OBO (Output Back Off) point.

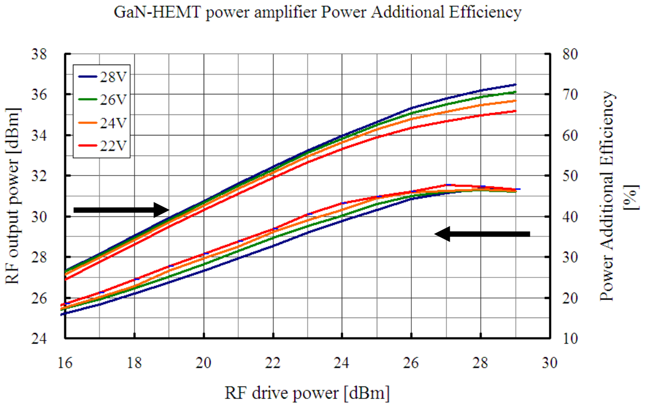
According to Fig.3.4, the highest efficiency, operating point depends on the power supply voltage, reached as high as approximately 47-48%. Moreover, this value was higher in all areas of several tens of percent as compared to the values of conventional amplifier.



F.g.3.2 AM-AM characteristics of the GaN power amplifier(Engineering Model)



F.g.3.3 AM-PM characteristics of the GaN power amplifier(Engineering Model)



F.g.3.4 Power Additional Efficiency characteristics of the GaN power amplifier(Engineering Model) Drain voltage is 28,26,24,22V.

4. Pre-distortion

We apply a digital pre-distortion technique [5, 6] to obtain nearly linear zed output signal with a high efficiency operation of the RF power amplifiers. As shown in Fig.4.1, this digital processing is performed in FPGAs after pulse shaping filtering.

The symbol rate we use is limited to 100Msps and the effective frequency bandwidth is about 100MHz, which is just 1.25% of the carrier frequency 8.16 GHz. The frequency dependences of AM-AM characteristics of Fig.6 (most left) are by less than 1dB while the nonlinearities are by 2-3 dB in terms of compression power level. The pre-distortion scheme is memory-less pre-distortion with look-up-tables, neglecting frequency dependence of the system. I and Q channel signals passing through pulse-shaping filters are pre-distorted with the inverse characteristics of AM/AM and AM/PM of the RF power amplifier. By performing the coordinate transformation before and after pre-distortion, dimensions of the LUTs is reduced to one.

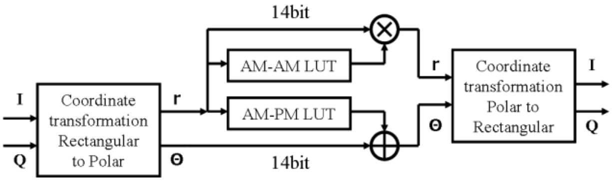


Fig.4.1 Pre-distortion function block

In order to increase the efficiency of the LUT, coordinate transformation blocks are set.

In order to define pre-distortion LUTs, it is necessary to measure whole system characteristics. Considering more than one nonlinear and frequency dependent devices are used in transmitter, we have to evaluate the transmitter in various conditions. As a result, we developed a new measurement system.

5. New transmitter measurement system

5.1 Overview

We have plans to use the pre-distortion technique, it is necessary to evaluate transmitter characteristics such as AM-AM and AM-PM curves in detail. In general, a transmitter, particular amplifiers in transmitter, is affected by temperature and transmitter generates heat. Therefore, the measurement system must be sufficiently quick. And, the characteristics we need for pre-distortion technique is the whole characteristics from base-band input to RF output. In addition, considering the purpose of measurement, high accuracy is not required. As sum of them, we developed a new base-band to RF measurement system.

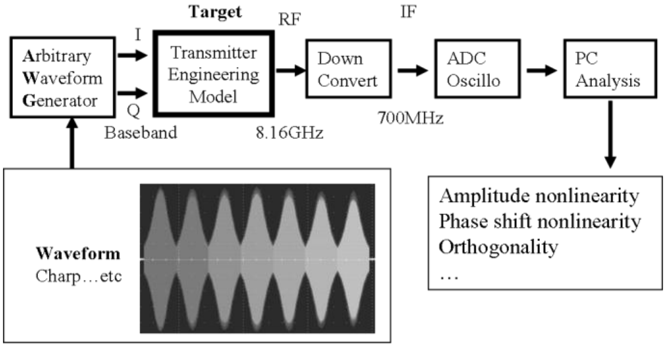


Fig.5.2.1 Measurement system block

5.2. Measurement scheme

In order to measure without affect from IMD, a single tone is required. By using the following formula, base-band signals allow to make frequency sweep.

Assume base-band frequency=ω_0, carrier frequency=ω_0, $I_0 = Q_0 = A_0$.

$$\begin{aligned} RF &= I(t) \times \sin(\omega t) + Q(t) \times \cos(\omega t) \\ &= I_0 cos(\omega_0 t) \times \sin(\omega t) + Q_0 sin(\omega_0 t) \times \cos(\omega t) \\ &= A_0 sin((\omega_0 + \omega)t) \end{aligned}$$

In analysis block, by comparing the signal with a reference signal, the analyzer calculates the characteristic properties such as AM-AM. The drift canceller block has two functions. The first is to cancel the time-varying characteristics that occur in the frame shorter than 1ms. And the second is to cancel the phase rotation. Thereby, even small phase shift can be detected.

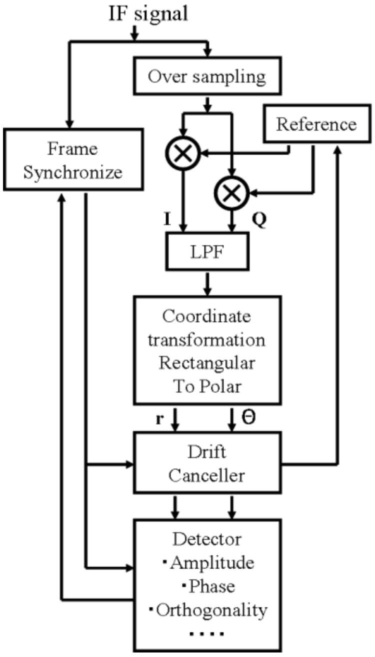


Fig.5.2.2 Analysis block of the measurement system flow chart

In addition, the difference between the value of the spectrum analyzer and the values obtained by this method was at most 0.2dB.

6. Transmitter engineering model and measurement/evaluation result

6.1. Transmitter engineering model

The EM is made for the purpose of evaluation of our pre-distortion algorithm, novel GaN-HEMT amplifier and high-speed digital circuits. As a transmitter of over 300Mbps, the EM has become very compact. We have started to improve and evaluate, and already obtained conclusions on some characteristics.

Table.6.1.1 Engineering model specifications

Weight	1.33kg
Size	120mm×120mm×73mm
Power consumption	18W
Avg. RF power	34dBm

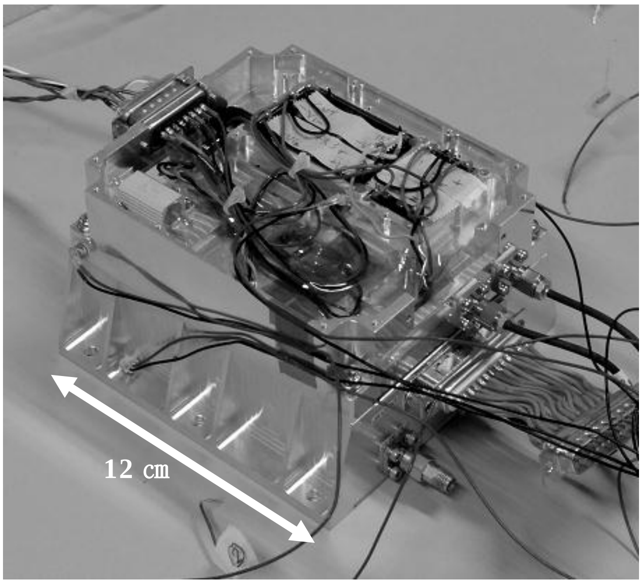


Fig.6.1.1 Photograph of the new transmitter
(engineering model include power supply)
1st floor: Analog RF block
2nd floor: Digital block

6.2. Measurement result (Analog characteristics)

The typical characteristics we have already obtained are shown figures below. Fig.6.2.1 shows AM-AM characteristics of each frequency, 150MHz bandwidth centered at 8.16GHz. The non-linearity is 3-4dB in the saturated region, whereas variation of the AM-AM characteristic is about 1.5dB. This result that the frequency dependence is much smaller than nonlinearity indicates that it may be enough just pre-distortion without memory effect.

Fig.6.2.2 shows AM-PM characteristics of each frequency. The phase shift depends on the amplitude is smaller than 8 degrees, and this value is very approximate to the results of a single power amplifier. We concluded that change in frequency distribution caused by correcting this property becomes low. This indicates that the recursive calculation for compensating the frequency characteristic is not important for pre-distortion.

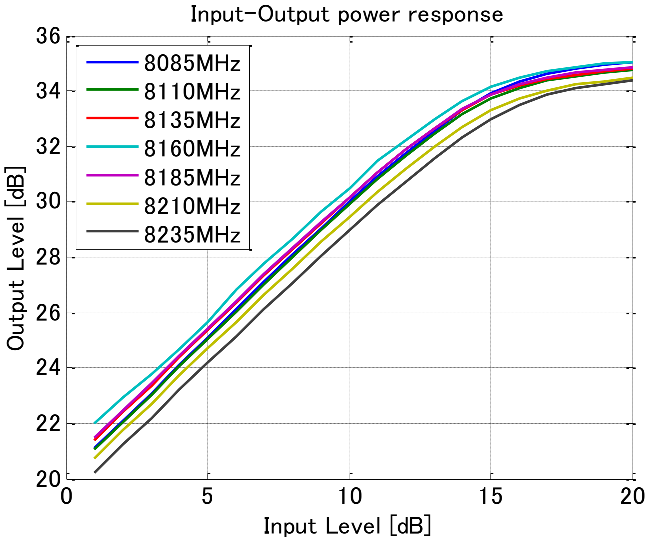


Fig.6.2.1 AM-AM characteristics
25MHz step

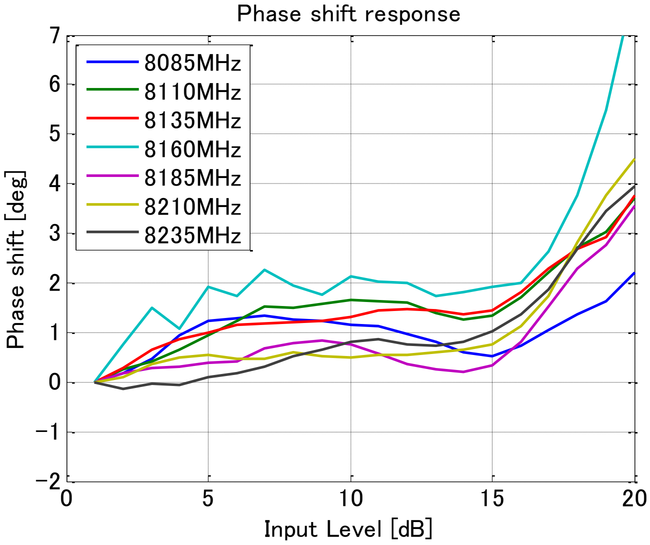


Fig.6.2.2 AM-PM characteristics
25MHz step

Fig6.2.3 is another aspect of Fig.6.2.1. This graph shows frequency dependency in each input level. The more signal levels, the smaller the frequency dependence. This characteristic that no stronger frequency dependence in non-linear regions indicates that the analog stage of the EM set is suitable for pre-distortion.

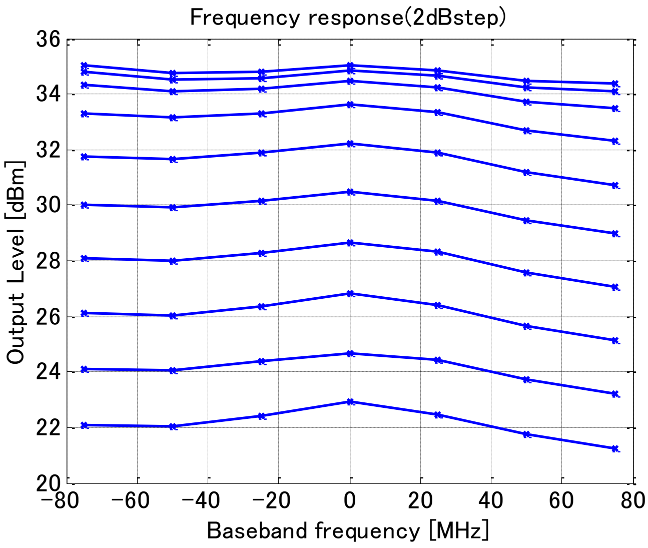


Fig.6.2.3 frequency response characteristics
2dB step base-band input

6.3. 16-QAM decode test result

We conducted a simple communication experiment without pre-distortion.

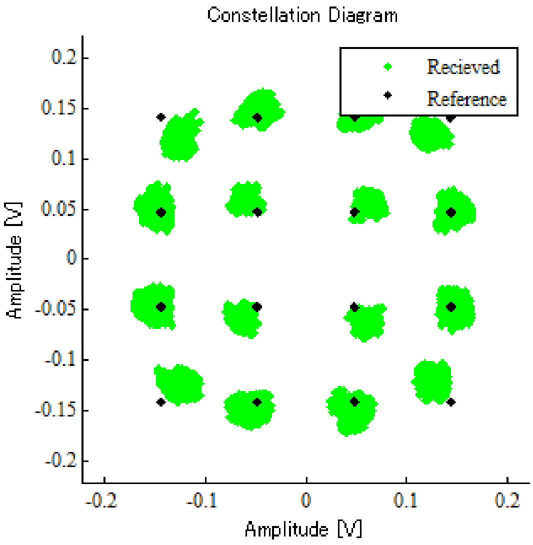


Fig.6.2.4 Constellation plot
100Msps, W/O noise
199992 symbols, OBO 3dB

Inter Symbol Interference (ISI) and constellation deviation was observed. Rms Error Vector Magnitude(EVM) is 12.8.

7. Conclusion

Our research has focused on an efficient and powerful, over 300Mbps X-band downlink system. In order to achieve both the signal quality and power saving, we have adopted optimized digital pre-distortion and novel GaN-HEMT power amplifier. We developed a new measurement method and got good results for pre-distortion. We got the confidence that our point is correct. And we will report advanced result in the conference.

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