Rectifier Conversion Efficiency Increase in Low Power Using Cascade Connection at X-band

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Abstract-This paper presents an efficiency increase method using the cascade connected rectifier network for low power operation in X-band. The presented cascade rectifier network is better for the large number of rectifier array, especially low power applications and has a simpler network than series connection network while producing a higher voltage than parallel connection network. The result shows 12% and 38% more power gained compared to series and parallel connection at 0 dBm and -3 dBm of input power respectively. Simulation conducted using Avago Technology HSMS-8101 schottky barrier diode and Taconic TLC-30-0200 substrate.

I. INTRODUCTION

Recently, wireless power transmission (WPT) and energy harvesting technology is being spotlighted as energy transmission and saving. [1]-[5] The key point of WPT application is composition of transmitting and receiving antenna array and RF-to-DC conversion efficiency. Especially, RF-to-DC conversion efficiency is the key factor that determines overall system efficiency. When low power is converted to DC, if received power could not overcome forward voltage drop of the diode, then RF-to-DC conversion efficiency becomes extremely low. Moreover, when low RF power is converted to DC, it is hard to gain high DC output voltage. This makes forward voltage drop become significant factor for conversion efficiency. To overcome this situation, there exists many kind of series connection to get high DC voltage. [4], [6] But in case of large number of rectifiers are connected, it is hard to realize series connection since its ground must be separated from each other or rectifying network should exists same plane of antenna to gives bias voltage to next antenna.

In transmitting and receiving array system, since received power pattern at receiving antenna is usually not uniform, elements which are positioned near edge of the antenna array receive relatively less power and it is inevitable in wireless power transmission system. Moreover, in high power application, matching point of diode is varies with input power. And to get a high power, rectifier is designed and matched for maximum power that usually received at the center of receiving array. In 2D array, since the bigger the array size, the number of element which are positioned near edge becomes larger, increase the efficiency of these elements is helpful for overall system efficiency. Presented cascade connection could increase conversion efficiency at low
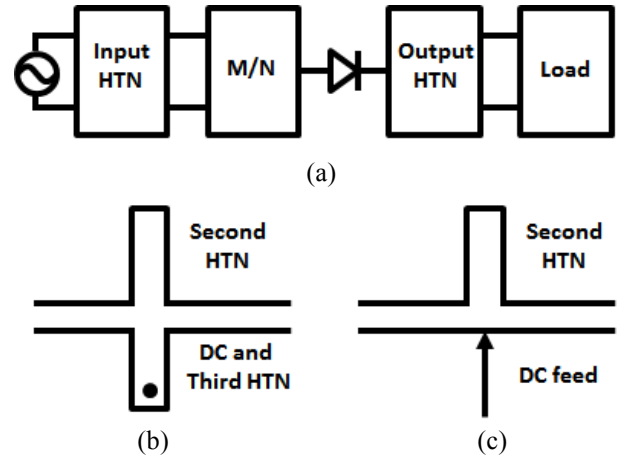

(a)

(b)   (c)

Figure 1. (a) Composition of single rectifier, (b) Detailed view of input HTN, (c) Modified input HTN for cascade rectifier network.

voltage that forward voltage drop of the diode is nonlinear and therefore helps increase the conversion efficiency of these elements. For such a reason, in the energy harvesting field which usually converts low power to DC power, this cascade rectifier network could increases RF-to-DC conversion efficiency of elements which are positioned not only near center but also positioned near edge.

In this paper, characteristics of single rectifier for cascading network, basic theory of parallel and series connection, properties of cascade rectifier network, and efficiency increase mechanism using diode characteristics are presented. Also, this paper deals with advantage of cascade rectifier network beside the parallel and series connection network.

II. RECTIFIER DESIGN

Basically, rectifier is consists of input and output harmonic termination network (HTN), matching network, and load as shown in Fig. 1 (a). HTN increases conversion efficiency by eliminating harmonics. In order to implement cascade network, DC biasing point is needed between RF feeding (or antenna) and rectifying diode. But basically, at input network, there is grounded stub as shown in Fig. 1 (b) that eliminates DC harmonic which is generated from nonlinear characteristics of diode, and this stub must be removed for DC bias. Thus, from second rectifier of cascade network, rectifier is redesigned by leaving the stub that eliminates
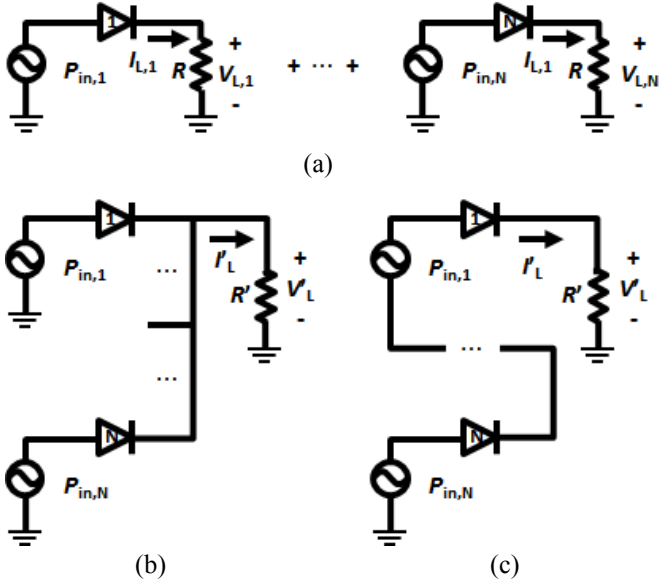
Figure 2. (a) Rectifier array which gets different input power each other and matched to same load resistance R, (b) parallel connection, (c) series connection.

second harmonic, and removing the stub that eliminates DC and third harmonic as shown in Fig. 1(c). The first rectifier of cascade network is same as basic single rectifier. In case of third harmonic is dominant over second harmonic, better efficiency can be achieved by leaving the stub that eliminates third harmonic only, and removing the stub that eliminates DC and second harmonic.

In this paper, every simulation is conducted by basic halfwave rectifier which is consists of single diode and single capacitor. And halfwave rectifier shows better conversion efficiency relatively low input power. [6]

The definition of the RF-to-DC conversion efficiency is [1]:

$$\eta_{\text{RF-to-DC}} = \frac{P_{\text{DC}}}{P_{\text{in}}} = \frac{(V_{\text{DC}})^2 / R_{\text{LOAD}}}{P_{\text{in}}} \quad (1)$$

Where P_{in} is input power to the rectifier, R_{LOAD} is the load resistance of the rectifier, and V_{DC} is the DC output voltage.

Since input power is not small signal, matching point varies with input power and very sensitive to circuit size and organization especially for high frequency applications. So, insensitive structure is required for stable fabrication and measurement. Radial stubs are recommended. In this paper, rectifier is matched to 0 dBm of input to shows increase of conversion efficiency better.

III. PARALLEL AND SERIES CONNECTION

The basic theory of parallel and series connection of rectifier can be explained by assuming output power out diode as current source. Suppose each rectifier is identical and matched to load resistance R for the maximum power transfer. Each rectifier gets different input power P_{in} as shown in Fig. 2

(a). Then the load resistance and the load voltage for the maximum power transfer for each connection method could be calculated as shown in below.

A. Parallel connection

For parallel connection, as shown in Fig. 2 (b), when the sum of both current and power from each rectifier are transferred to load resistance, the maximum power transfer occurs. Load resistance and load voltage of parallel connection network can be calculated by following equations.

$$R' = \frac{\sum_i V_{L,i}^2}{\left(\sum_i V_{L,i}\right)^2} R \quad (2)$$

$$V_L' = \frac{\sum_i V_{L,i}^2}{\sum_i V_{L,i}} \quad (3)$$

Note that, as more rectifiers are connected in parallel, load resistance becomes smaller and it causes more current flows at load resistance. Thus, for a large number of arrays, overcurrent may flows across the load resistance.

B. Series connection

For series connection, as shown in Fig. 2 (c), when the sum of both voltage and power from each rectifier are transferred to load resistance, the maximum power transfer occurs. Load resistance and load voltage of series connection network can be calculated by following equations.

$$R' = \frac{\left(\sum_i V_{L,i}\right)^2}{\sum_i V_{L,i}^2} R \quad (4)$$

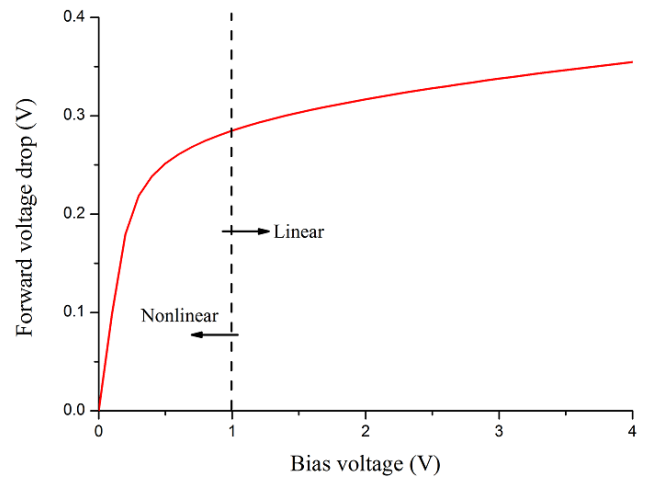$$V_L' = \sum_i V_{L,i} \quad (5)$$

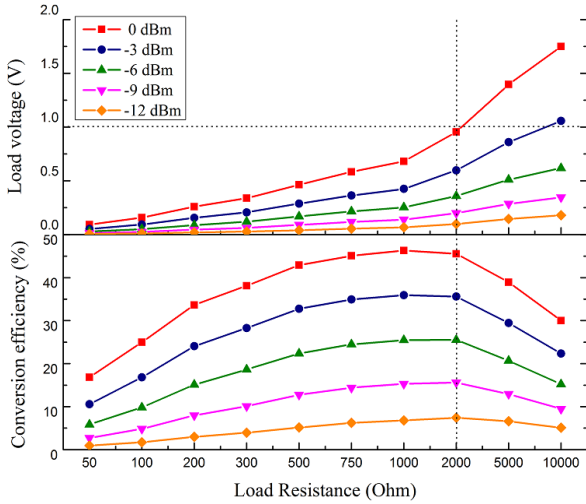Figure 3. Forward voltage drop versus bias voltage.

Figure 4. Load voltage and maximum conversion efficiency for each load resistance for each input power.

Note that the more rectifiers are connected in series, the higher the load resistance is.

When consider the maximum conversion efficiency, the overall output voltage of parallel connection cannot be higher than the maximum output voltage of rectifier in parallel connection network. For the series connection network, the output voltage could be higher, but each ground of rectifier must be separated from each other. If connection efficiency is considered, the overall conversion efficiency of network could be lower. Because for the parallel and series connection, power across the load resistance is calculated by linear summation of each rectifier, conversion efficiency lies between minimum and maximum efficiency of rectifier in the connection network.

IV. CASCADE CONNECTION

The key point of increase of conversion efficiency in cascade network is nonlinearity of diode. If forward voltage drop lies in linear region, it is hard to expect increase of conversion efficiency since output voltage of previous stage is dropped again when it biased to diode, and this forward voltage drop is proportional to bias voltage in linear region as shown in Fig. 3. On the other hand, forward voltage drop is nonlinear for low DC bias. That is, little DC bias makes RF signal overcomes forward voltage drop easier and it causes increase of conversion efficiency. But from the second stage of cascade network, since DC and third harmonic elimination stub does not exists as shown in Fig. 1 (c), conversion efficiency of second stage itself could be lower than the first stage of cascade network. Moreover, DC harmonic from diode of the second stage makes lower the DC bias which is output voltage of the first stage. But power of harmonic is proportional to input power and then efficiency loss is relatively low at low input power, therefore cascade network will increase the conversion efficiency. Thus, unlike conversion efficiency is bounded in parallel and series connection, overall conversion efficiency of cascade network
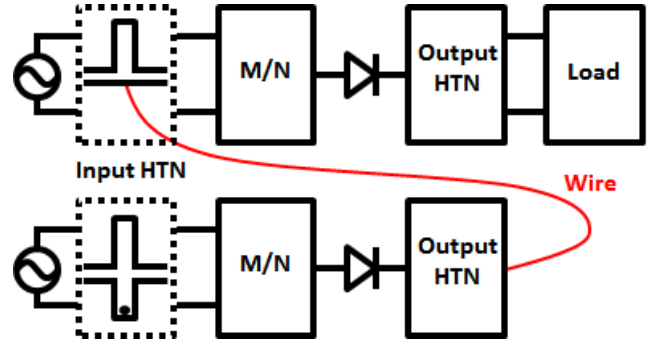

Figure 5. Composition of 2-stage cascade rectifier.

could be higher than the maximum conversion efficiency of single rectifier in cascade network. If rectifiers are matched to 0 dBm of input power, then 2000 ohm of load impedance makes maximum power transfer and its load voltage is below 1 V as shown in Fig. 4. Since input power is relatively low, unlike parallel and series connection, variation of optimum load resistance of cascade connection is small. Cascade network can be composed by removing load resistance of the first stage and DC HTN of the second stage, and biasing DC output voltage of the first stage to the second stage as shown in Fig. 5. Three and more cascade network could be composed by biasing DC output voltage of previous stage to next stage. Wire is used for DC feeding method since in X-band, it is hard to use chip inductor as RF choke. The equivalent circuit model for long straight wire over the ground is series connected resistor and inductor. And its value for equivalent circuit model can be calculated by following formula. [8]

$$R = \rho \frac{l}{A} \tag{6}$$

$$L = \frac{\mu}{2\pi} \ln\left(\frac{4h}{d}\right) \tag{7}$$

Where, ρ is resistivity, A is cross section area of wire, d is diameter of wire and h is distance between ground and the center of wire. Assume that $h > 1.5d$.

Since distance between rectifiers is usually short, resistance of wire is negligible. And since wire over the ground prevents RF guiding, the wire could be good RF choke in high frequency operations. Therefore, only DC power exists in wire. Although wire is open circuit in the view point of RF, when it is biased to rectifier, there is RF power at DC bias point, and it may influence matching network and harmonic termination. Conversion efficiency for each input power and each number of cascade stage is shown in Table I. Load resistance of every cascade network in Table I is fixed to 2000 Ohm. Note that since input power is low, conversion efficiency is relatively low and thus load voltage is also low. But unlike conversion efficiency of parallel and series

TABLE I

SUMMARY OF CASCADE RECTIFIER

Output voltage and Conversion efficiency				
Input power	Single	2 stage	3 stage	4 stage
0 dBm	0.79 V / 31%	1.18 V / 35%	1.42 V / 34%	1.58 V / 31%
-3 dBm	0.41 V / 16%	0.68 V / 23%	0.83 V / 23%	0.93 V / 22%
-6 dBm	0.17 V / 6%	0.33 V / 11%	0.42 V / 12%	0.48 V / 11%
-9 dBm	0.05 V / 0.9%	0.12 V / 2.7%	0.16 V / 3.2%	0.18 V / 3.2%

connection is remains same or degraded as more rectifiers are connected, cascade connection could increases conversion efficiency as connected more. For example, output power of 2 stage parallel or series network for input power of -3 dBm is 168 μW, but in cascade connection, 231 μW of output power could be achieved and its 38% more than parallel and series network.

As input power is lower, the increase rate of conversion efficiency is higher. And it is due to nonlinear characteristic of diode as explained previously. Note that, increase the number of stage is not always causes increase of conversion efficiency. Because DC harmonic that caused by each stage is lowers the output voltage or DC bias. For example, DC harmonic caused by the third stage could lower the output voltage of the second stage, and this makes degradation of output voltage of the first stage. Therefore, as more rectifiers are connected in cascade, the output voltage of the first stage keeps degrading. After all, the first stage could not act as rectifier at all and then overall conversion efficiency of cascade network is degraded rapidly. Since DC harmonic is proportional to input power, increase of the number of cascade stage is not necessary as input power of DC bias is getting higher.

V. CONCLUSION

In this paper, increase conversion efficiency method using cascade connection is presented. The maximum increase of conversion efficiency is 12%(2 stage), 38%(2 stage), 103%(3 stage), 340%(3 stage) for 0 dBm, -3 dBm, -6 dBm, -9 dBm of input power, respectively, while conversion efficiency of parallel and series connection does not increase. At cascade network, increase of conversion efficiency is high, but since input power is low, the output power itself is not that high. Therefore gathering these power helps increase of overall system efficiency especially energy harvesting or WPT applications.

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