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Gain flattening technique for optical wireless front-end receiver considering various large window photodetectors

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ABSTRACT

A novel gain flattening technique for an optical wireless front-end receiver structure involving a bootstrap transimpedance amplifier (BTA) integrated with a MEMS variable feedback capacitor has been demonstrated. The MEMS varicap replaces a fixed capacitance as the feedback element in the front end system to optimize the performance of the BTA in terms of its frequency response. The implementation of the MEMS device with a BTA optical front-end receiver was verified using CoventorWare ARCHITECT. The simulation results showed that the approach can significantly flatten the peaking gain by up to 14 dB, when considering a system with various photodetector capacitances, ranging in value from 100 pF to 1 nF.

1. Introduction

With the explosive growth in commercial wireless telecommunication systems, optical wireless has received considerable attention because of the opportunities it offers in terms of requirements for broadband communications. Optical wireless has evolved, and the IEEE 802.11 IR standard for wireless local area networks (LAN) is a result of realizing the importance of the approach [1]. When considering communication systems in general, the receiver has to be one of the crucial elements to be considered. In optical wireless, as with other systems, the link budget must be considered, and the receiver, especially at its front end, is significant in determining of the overall system performance. Unfortunately, in optical wireless (or FSO), the large detection area required for the photodetector, in order to increase the system's sensitivity, inevitably incurs high input capacitance. Generally, large area photodetectors have a typical capacitance from 30 pF to 3 nF, but a lower capacitance than this is essential to achieve a wide bandwidth. There has been considerable effort to obtain the required bandwidth for such large capacitance devices [2–5], but less consideration has been given to front end structures with a photodetector capacitance of up to 1 nF. Therefore, in this paper, we propose an optical front end structure that is able to adapt to a range of photodetector capacitances by integrating a BTA with a MEMS variable capacitor. The BTA concept was introduced by Green and McNeill [6], as a means of beneficially combining two already established techniques for firstly reducing of the effect of a capacitive source, and secondly interfacing a photodiode to a subsequent front end amplifier.

In this work, MEMS technology was chosen for the variable capacitor design because it has the potential of realizing variable capacitors with a performance that is superior to that of varactor diodes and MOS capacitors, in properties such as nonlinearity and loss. To date, MEMS variable capacitors have been actively researched for achieving high Q-factors, tuning ratios and self resonance frequency [7]. Amongst the possible MEMS variable capacitor structures, MEMS parallel plate capacitors have been commonly developed [8–10]. Such capacitors often consist of a suspended top plate that can be electrostatically actuated via an applied voltage to change the capacitance between the plates. In this work, a three, parallel-plate capacitor was utilized as a variable feedback element, as the requirement was for a wide tuning range for the BTA system.

In the next section, the operating principle and system architecture, including the BTA front-end receiver configuration and three parallel-plate MEMS variable capacitor, will all be described. The MEMS variable capacitor design, and its analysis, in order to achieve suitable tuning range for implementation with the BTA circuit, will be discussed in Section 3. Section 4 provides details of the simulation result and discussion.

2. Operation principle and system architecture

The basic architecture of the proposed optical wireless front-end receiver is implemented by combining the bootstrap

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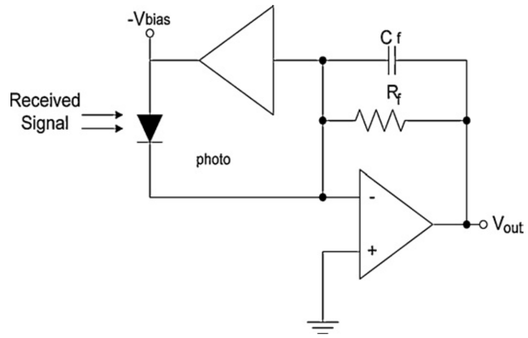

Fig. 1. Shunt and floating source BTA circuit arrangement.

transimpedance amplifier with a MEMS variable feedback capacitor. The BTA consists of a current-to-voltage converter applied to the photodiode current, and a feedback element to ensure the circuit's stability. The effect of the bootstrapping is to produce two almost complementary signals, V_c, at either side of the photodiode [11]. This has the effect of ensuring that the photodiode's internal capacitance does not absorb current significantly especially at higher frequencies, as the $\{dV_c/dt\}$ component must also be reduced across the photodiode by the bootstrap action, where C is the photodiode capacitance.

Consequently, the effect of high photodiode capacitance seen by the signal is reduced according to the feedback gain of the configuration. The basic circuit of the BTA is illustrated in Fig. 1 in which it shows the shunt circuit arrangement.

An effect of the high photodetector capacitance associated with a large window photodetector required in an optical wireless system is that it will produce peaking gain that affects the stability of the circuit, and causes undesirable ringing in digital systems. With regard to the requirements of the system, the peak in the frequency response begins to appear and increase as the photodetector capacitance is increased. In this work, a variable feedback capacitor has been applied, together with a feedback resistor as the feedback element, instead of just a fixed feedback capacitor, as reported in [12]. MEMS varicap technology was utilized in which the designed variable capacitor used a widely-adopted polysilicon surface micromachining structure known as MUMPs. The MUMPS technology has the same general features as a standard surface micromachining process [9]. Polysilicon is used as the standard layer, deposited oxide is used as the sacrificial layer, and silicon nitride is used as the electrical isolation between the polysilicon and substrate.

The variable feedback capacitor needed in the BTA circuit must have a large tuning range. Therefore, the variable capacitor chosen was one which consists of three parallel plates and which exhibits a wider tuning range, as reported previously by Dec et al. [10]. The conceptual model of a three parallel plate MEMS varicap is illustrated in Fig. 2. The top and bottom plates are fixed mechanically, whilst the middle plate is suspended by two springs, each with a spring constant of $k/2$.

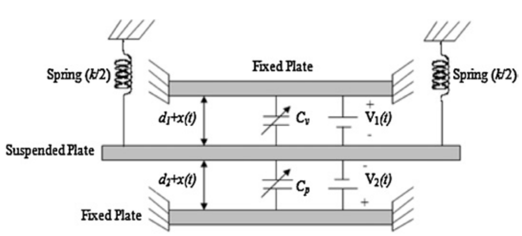

Fig. 2. The conceptual model of the three parallel-plate MEMS varicap.

The designed three parallel plate MEMS varicap consists of two capacitances; the variable capacitor, C_v and parasitic capacitor, C_p. In this kind of structure, the two varicaps are in parallel, and only one was actually used in the application (C_v), and the other was considered as a parasitic (the one with smallest capacitance was designated as C_p). In general, the parallel plate capacitance is clearly given by:

$$C = \frac{\varepsilon A}{d + x} \tag{1}$$

where ε is the dielectric constant, A is the area of the capacitor plates, d is the separation of the capacitor plates under zero-bias voltage, and x is the displacement of the suspended plate from its original position when a bias voltage is applied across the plates. The maximum capacitance that this capacitor can be tuned, when V_1 is applied, is given by:

$$C_{\max} = \frac{\varepsilon A}{d_1 - d_1/3} = \frac{\varepsilon A}{2d_1/3} = 3C/2 \tag{2}$$

On the other hand, the minimum capacitance that this capacitor can be tuned, when V_2 is applied, is given by:

$$C_{\min} = \frac{\varepsilon A}{d_1 + d_1/3} = \frac{\varepsilon A}{4d_1/3} = 3C/4 \tag{3}$$

3. MEMS varicap design and analysis

The bootstrap circuit utilizing feedback capacitance was originally introduced to ensure circuit stability. However, in designing a BTA circuit for a particular optical receiver, the optimum value of the feedback capacitor must be found in order to maximize the bandwidth performance of the system. Therefore, the main emphasis of this work was on the analysis of the appropriate value of feedback capacitor for optimizing the frequency response of the BTA circuit. As such, a MEMS varicap was chosen for the feedback

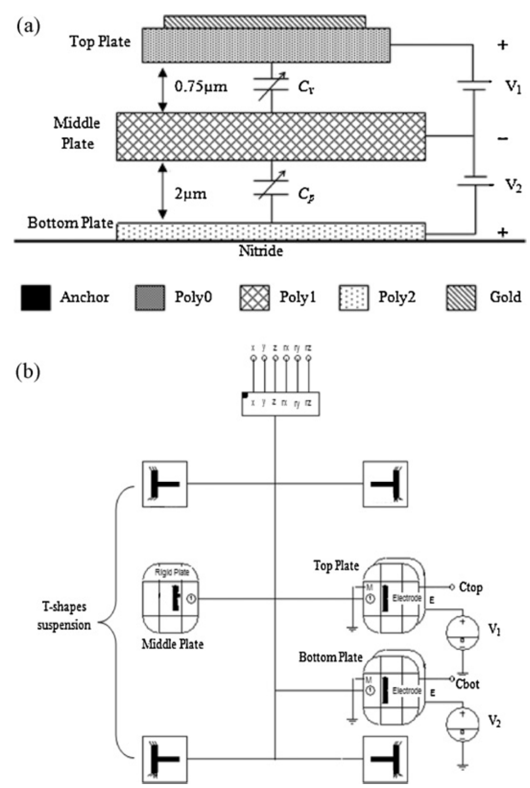

Fig. 3. (a) The cross section view, and (b) the schematic circuit of a three parallel plate MEMS variable capacitor.

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capacitor due to its constant phase noise properties, low parasitic losses, low interconnection requirements, and reduced complexity due to the monolithic integration.

The analysis began with the MEMS varicap design. It consisted of a rigid plate as a middle plate (poly 1), a bottom electrode (poly 0) and a top electrode (poly 2), as shown in Fig. 3. The T-shaped suspension was connected to the middle plate. The size of the capacitor was 400 μm × 400 μm, with an air gap between the top plate and middle plate of 0.75 μm, and an air gap between the middle plate and bottom plate of 2 μm, as shown. In addition, to ensure the oxide between the capacitor plates was fully etched, 324 holes were made in the capacitor plates so as to ensure rapid release of sacrificial layers [7]. Without bias voltages applied ($V_1 = 0$ and $V_2 = 0$), there was no movement occurring at the middle plate. Therefore, the gap between those three plates did not change. By employing Eq. (1), in the prototype, the nominal capacitance of the varicap was found to be 1.885 pF. However, when a bias voltage, V_1, was applied, the resultant electrostatic force caused the middle plate to be attracted toward the top plate and away from the bottom plate. On the other hand, the middle plate moved toward the bottom plate and simultaneously away from the top plate when a bias V_2 was applied. Thus, varicap tuning was achieved in which the value of C_v and C_p were changed, depending on the gap between middle plate, and top and bottom plates. Fig. 4 shows the tuning characteristics of the MEMS varicap when V_1 and V_2 were applied, respectively.

By referring to the results obtained, it was found that the maximum capacitance achieved was approximately 2.51 pF at $V_1 = 1.6$ V, whereas the minimum capacitance was 1.03 pF at $V_2 = 7.1$ V. Therefore, the capacitance changed from 1.03 pF to 2.51 pF, showing a global tuning ratio of 145% for actuation voltages from 1.6 V to 7.1 V. Hence, the wide tuning range exhibited by the modeled MEMS variable capacitor was found to be suitable for use in the BTA configuration. Table 1 lists the value of variable capacitance, C_v, according to the applied bias voltage, V.

4. Results and discussion

In order to compare the performance of an optical wireless front end receiver both with and without a MEMS variable feedback capacitor, both designs were simulated together. This was done using CoventorWare ARCHITECT, using the equivalent circuit theory with a system level approach. Fig. 5 illustrates the peaking gain produced by the front end system without the MEMS variable feedback capacitor, and when considering various photodetector capacitances from 100 pF to 1 nF.

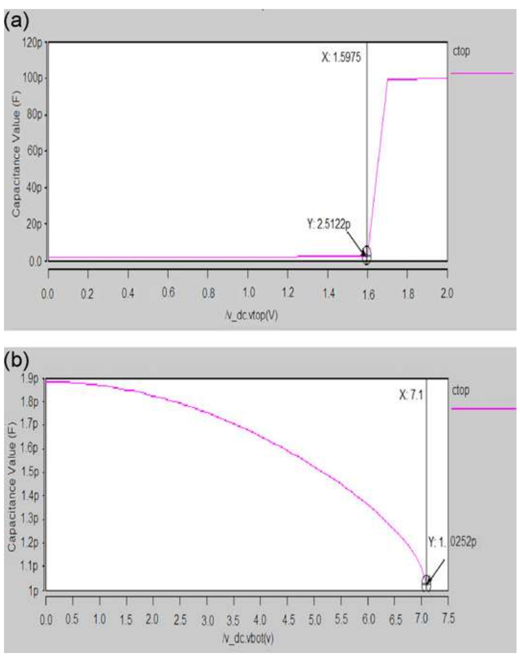

Fig. 4. (a) Maximum capacitance before pull in when V_1 was applied and (b) minimum capacitance before pull in when V_2 was applied.

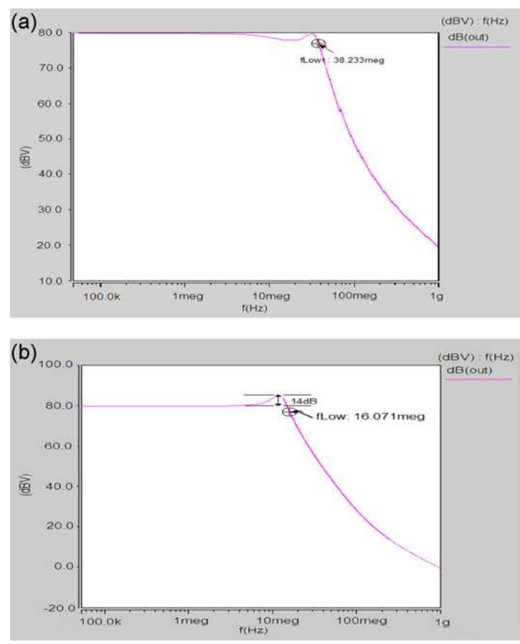

Fig. 6. Frequency response of the BTA when coupled with: (a) 100 pF and (b) 1000 pF PIN photodetector.

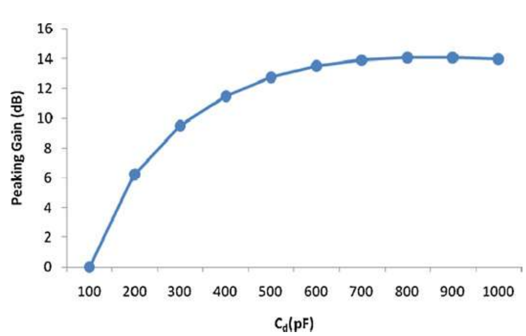

Fig. 5. Peaking gain versus various PIN photodetector capacitance, C_d, in the front-end system without the MEMS variable capacitor.

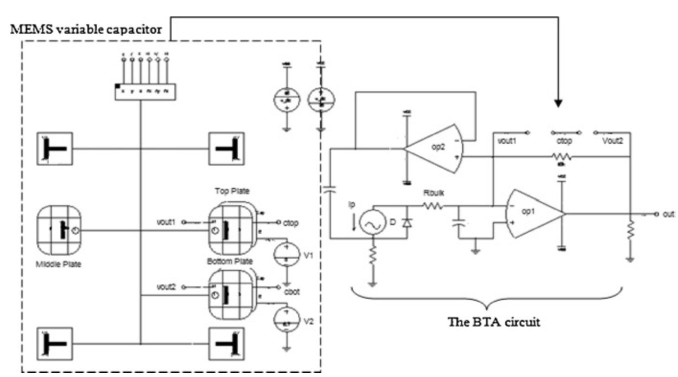

Fig. 7. The schematic of the BTA circuit employing a MEMS varicap.

Table 1
Variable capacitance found for a particular bias voltage.

	V_2			V_1					
Bias voltage (V)	6.7	4.45	0	0.96	1.22	1.38	1.48	1.54	1.59
C_v (pF)	1.2	1.6	1.9	2.0	2.1	2.2	2.3	2.4	2.5

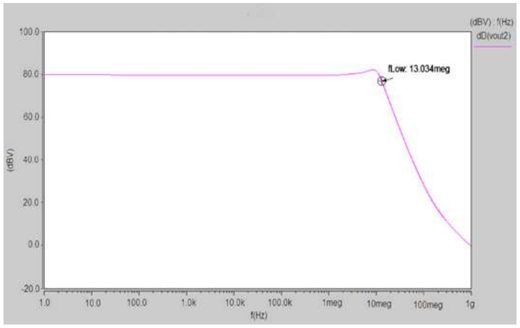

Fig. 8. Frequency response of the integrated BTA with MEMS varicap coupled to a 1 nF PIN photodetector.

In the front-end system coupled to a 100 pF photodetector capacitance, the system produced a stable response without peaking gain. However, the peaking gain began to appear and increased with higher photodector capacitance, when this was varied from 100 pF to 1 nF. Thereafter, the BTA system, using 100 pF and 1 nF photodetector capacitance, was then simulated for the lowest peaking gain and the highest value, at 14 dB, to investigate the frequency response produced. Fig. 6 shows the frequency response of the front end system without the MEMS varicap coupled to 100 pF and 1 nF photodetector capacitance, respectively.

With reference to the responses above, it was observed that the BTA system with 100 pF photodector capacitance produced a reponse with no peaking gain. On the other hand, the BTA system with 1 nF photodetector capacitance produced the highest peaking gain, as expected. Thus, the integrated BTA systems with MEMS variable feedback capacitor was investigated in order to flatten the peaking gain, and hence provide the front end system with a stable frequency response.

For the proposed design, the MEMS varicap replaced the fixed feedback capacitor in the BTA circuit as the feedback element, as shown in Fig. 7. In order to determine the optimum value of variable capacitance, analysis was carried out to determine the feedback capacitance that would produce a stable response without peaking gain. For this analysis, the optimum variable capacitance value found is listed in Table 1, therefore giving the value used to define the properties of the MEMS varicap.

Meanwhile, by considering the highest peaking gain that it is required to flatten out, a configuration involving a 1 nF photodetector capacitance in combination with the BTA circuit was then simulated. The MEMS varicap was adjusted to have a capacitance of 2.5 pF to improve the fidelity of the frequency response, as shown in Fig. 8. From the graph, it is observed that the 14 dB peaking gain was flattened, so that the frequency response, and thus stability of the circuit, were improved.

Previous significant work in this subject was reported by Idrus et al. [12] which demonstrated the BTA circuit approach for optical wireless applications. As reported [12], the bandwidth provided by the BTA circuit with no peaking gain was 33.4 MHz, when considering 100 pF photodetector capacitance. However, in that work, it was seen that significant peaking gain began to appear for much higher photodetector capacitances. As far as this new reported work is concerned, a similar front-end design was adopted, but the fixed feedback capacitor was replaced by a MEMS varicap. Providing a gain flattening capability of up to 14 dB, the new approach demonstrates conclusively that, integrating a BTA circuit design with a MEMS varicap in the front-end design for optical wireless applications is beneficial significantly to overall control and optimization of front ends using this configuration.

5. Conclusion

In this work, we reported a technique to flatten the gain of optical wireless front-end receiver considering various photodetector capacitances. This technique implemented the integration of three parallel plate MEMS variable capacitor with the BTA system, well known as a bandwidth enhancement technique for optical wireless front end receivers. By employing a MEMS variable feedback capacitor in the BTA system, it was found that this approach is effective in flattening the unwanted peaking gain up to 14 dB, when considering applications requiring large area (and thus capacitance) photodetectors.

References

[1] A. Mahdy, J.S. Deogun, Wireless optical communications: a survey, Proc. IEEE Wireless Commun. Netwrk. Conf. (2004) 2399–2404.
[2] B. Analui, A. Hajimiri, Bandwidth enhancement for transimpedance amplifiers, IEEE J. Solid-State Circ. 39 (2004) 1263–1270.
[3] R.Y. Chen, T.S. Hung, C.Y. Hung, A CMOS infrared wireless optical receiver front-end with a variable-gain fully-differential transimpedance amplifier, IEEE Trans. Consum. Electron. 51 (2005) 424–429.
[4] Z. Lu, K.S. Yeo, J. Ma, M.A. Do, W.M. Lim, X. Chen, Broad-band design techniques for transimpedance amplifiers, IEEE Trans. Circ. Syst. I 54 (2007) 590–599.
[5] Y. Zhang, V. Joyner, R. Yun, S. Sonkusale, A 700 Mbit/s CMOS capacitive feedback front-end amplifier with automatic gain control for broadband optical wireless link, Proc. IEEE Int. Symp. Circ. Syst. (2008) 185–188.
[6] R.J. Green, M.G. McNeill, The bootstrap transimpedance amplifier - a new configuration, IEE Proc. Circ. Syst. 136 (1989) 57–61.
[7] H.S. Lee, Y.J. Yoon, J.B. Yoon, High-Q, tunable-gap MEMS variable capacitor actuated with an electrically floating plate, Proc. IEEE Int. Conf. Micro Electro Mech. Syst. 21 (2008) 180–183.
[8] M.B. Kassem, R.R. Mansour, A high tuning range MEMS variable capacitor using carrier beams, Can. J. Electr. Comput. Eng. 31 (2006) 89–95.
[9] K. Tommy, K. Tsang, M.L. El-Gamal, Micro-electromechanical variable capacitors for RF applications, Proc. Midwest Symp. Circ. Syst. 45 (2002) 25–28.
[10] A. Dec, K. Suyama, Micromachined electro-mechanically tunable capacitors and their applications to RF IC's, IEEE Trans. Microw. Theor. Tech. 46 (1998) 2587–2596.
[11] J. Graeme, Photodiode Amplifer: Op Amp Solutions, McGraw-Hill, New York, 1995, ISBN 0-07-024247-X.
[12] S.M. Idrus, N. Ngajikin, N.N.N.A. Malik, S.I.A. Aziz, Performance analysis of bootstrap transimpedance amplifier for large windows optical wireless receiver, Proc. Int. RF Microw. Conf. (2006) 416–420.

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