

Design and Analysis of High-Gain Over-Moded Microwave Pulse Compression System

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Abstract—In order to increase the power gain of the microwave pulse compression system, a high-gain over-moded microwave pulse compression system has been found first time for the rectangular TE_{1,0,20} resonant mode at 2.920GHz in S-band. The calculation results show that the physical model has an excellent physical performance: In the optimal resonant state, the power gain has reached up to 280.04:1.00. Relative the traditional physical model, the power gain increased by 51.86%; In the optimal resonant state, the energy storage efficiency of the over-moded system has also reached up to 88.91% at 2.920GHz for the rectangular TE_{1,0,20} resonant mode. Relative the traditional physical model, the efficiency increased by 23.33%; Another important conclusion is that the power gain is very sensitive to the deviations of the resonant cavity length and output waveguide position from their optimal values. For example, the power gain will decrease by 61.45% to 67.17% for the -0.10mm to +0.10mm length deviation of the resonant cavity. It is very important to the theoretical and experimental studies; Because of the universality of this high-gain over-moded physical model, the microwave pulse compression system and over-moded technology can be applied directly to X, Ku, and Ka band with a high-power gain for the potential application to the future extremely-high energy collider and other scientific researches.

Index Terms—microwave pulse compression, over-moded cavity technology, high power microwave, HPM

I. INTRODUCTION

AFTER the discovery of Higgs boson, scientists in the fields of high energy physics and accelerator physics try to build the next generation of ultra-high energy collider at 250~500GeV for e^-e^+ collision and 50~100TeV for p-p collision[1-4] to explore the physics at the extremely limit, just as proposed Future Circular Collider at CERN of

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Europe[1] and at IHEP of China[2], Next Generation Linear Collider at SLAC of USA[3], and International Linear Collider at KEK of Japan[4]. Thus, microwave pulse compression technology has been investigated widely recently years in theory and experiment in P-band, L-band, S-band, and X-band[5-17] in the fields of high energy physics, nuclear physics, accelerator physics, and microwave science and technology because the high power microwave pulse is the unique driven-source of the next generation collider.

Today, the peak power of 500~600MW and pulse width of 250ns ultra-high power microwave pulse has been generated successfully in X-band with the SLED technology by the scientists at SLAC of USA[9, 12, 18-19]; And, based on the SES (Switched Energy Storage) technology, the output pulse of 1GW/5ns in S-band and 165MW/20ns in X-band have also been successfully generated by scientists in Russia[14-16] and in USA[5-8]. But, the experimental results show that the maximum power gain of the SLED technology has not reached to the theoretical limit of 9.0:1.0; the maximum gain of the SES technology is at 20:1 in X-band and 100:1 in S-band respectively.

Although the great progress has been made in the recent years, the scientists in these fields are still trying to discovery new way to increase the power gain of the compressed microwave pulse further. In the research, we have found a new high-gain over-moded microwave pulse compression system that has a excellent physical performance for the rectangular TE_{1,0,20} mode at 2.920GHz in S-band, and its power gain has reached up to 280.04:1.00. In this letter, the high-gain over-moded physical model will be described in section-II first; Then, the calculation results in the optimal resonant state are given, and compared with the traditional physical model; Finally, analyze the affections of the resonant cavity length deviation and output waveguide position deviation to the system power gain, energy storage efficiency and the electric field intensity of the standing-wave in the resonant cavity; Conclusion is at the end.

II. PHYSICAL MODEL AND SIMULATION RESULTS

The physical model of the high-gain over-moded microwave pulse compression system suggested in this paper is shown in Fig.1. Different from the traditional SES-physical model, the microwave resonant cavity and the output waveguide in Fig.1 are all designed in form of over-moded dimensions.

The main purpose of the over-moded resonant cavity designed in this way is at trying to increase the Q-value of the resonant cavity in the stage of energy storage, and decrease the absolute electric field intensity of the standing-wave in the resonant cavity to expand the power capacity of the resonant cavity; The output waveguide designed in the form of over-sized dimension is to match the characteristic impedance of the output waveguide with the compression cavity to realize a full release of the stored energy from the compression cavity in the stage of the energy release while the cavity switch is closing;

The coupling window is designed in form of rectangular shape with dimension of 19.80mm×34.04mm×3.00mm (width×height×length). It was at the central axis-symmetrical position of the over-moded resonant cavity to prevent from the generations of the other models in the resonant cavity during the energy storage and only keep the rectangular TE_{1,0} resonant mode exist; In this high-gain over-moded system, the the cross-sections of the resonant cavity and the output waveguide were extended from the traditional dimensions a×b=72.14mm×34.04mm to a×b=72.14mm×68.08mm simply. The other parameters values in Fig.1 still keep at L₀=20×(λ_g/2), L₁=(λ_g/2), L₂=(λ_g/4), and 72.14mm×34.04mm for the input waveguide in theory. Where, the λ_g is the waveguide wavelength of the over-moded resonant cavity at 2.920GHz for the rectangular TE_{1,0,20} resonant mode. It will be shown that a little simply breaking to the traditional concept will result in great progress to the power gain for the microwave pulse compression system.

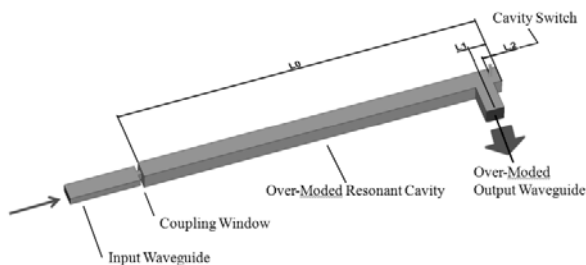


Fig. 1. Physical model of SES high-gain over-moded microwave pulse compression system for the rectangular TE_{1,0,20} resonant mode at 2.920GHz in S-band.

For the high-gain over-moded physical model in Fig.1, it has been studied with the high-frequency electromagnetic simulation software CST in order to get the maximum power gain for the rectangular TE_{1,0,20} resonant mode at 2.920GHz in S-band. This is because the maximum power gain determines directly the physical property and potential application value of the this new physical model.

But, the power gain is determined directly by the peak electric field intensity of the standing-wave in the resonant cavity; The peak electric field intensity of the standing-wave is controlled by the coefficient of the coupling window and the efficiency of the resonant cavity energy storage; The

coefficient and the efficiency are all related with the S-parameters of the over-moded microwave pulse compression system, or structure parameters values.

Thus, in the numerical simulation, the structure parameters are optimized first by the optimization search method. The aim of the optimization is to increase the electric field intensity of the standing-wave gradually until the microwave pulse compression system approaches to the maximum peak power. The state with the optimal parameters values is called the optimal resonant state.

In the numerical simulation, the conductivity of the copper well for the resonant cavity, coupling window, and input/output waveguide is set at $\sigma=5.81 \times 10^7$ S/m. The peak power of the input microwave pulse through the input waveguide is set at P_{in}=0.50W. The simulation runs in frequency domain.

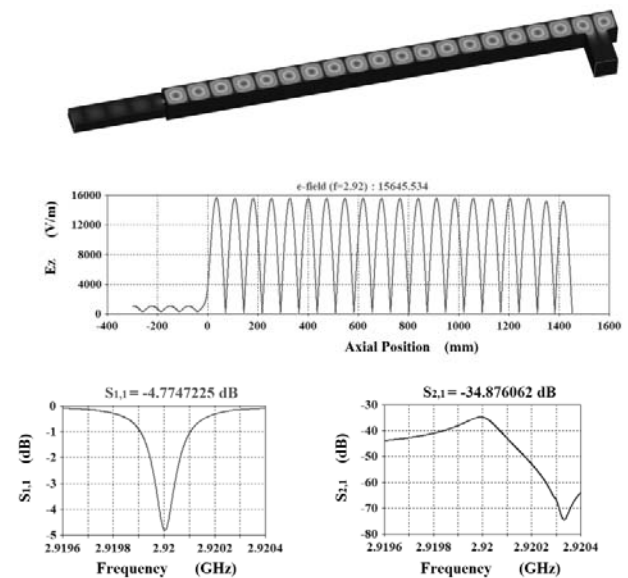


Fig. 2. Simulation results of the over-moded microwave pulse compression system for the rectangular TE_{1,0,20} resonant mode at 2.920GHz.

Today, the simulation results show that there is an optimal resonant state for the high-gain over-moded microwave pulse compression system. In the optimal resonant state, the coupling window has a dimension of 19.80mm×34.04mm×3.00mm (width×height×length), and L₀=1452.90mm, L₁=69.40mm, L₂=34.70mm for the optimal system; In Fig.2, it was shown the 3D-standingwave distribution of the system in the resonant state, 2D-distribution of the standing-wave electric field intensity along the cavity axis, and the S-parameter variation versus the frequency in the optimal resonant state.

In order to compare the physical performance of this new high-gain over-moded physical model with the traditional physical model (the cross-sections of resonant cavity, output waveguide and the input waveguide are all set with 72.14mm×34.04mm), the corresponding simulation results in

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its optimal resonant state was also shown in Fig.3.

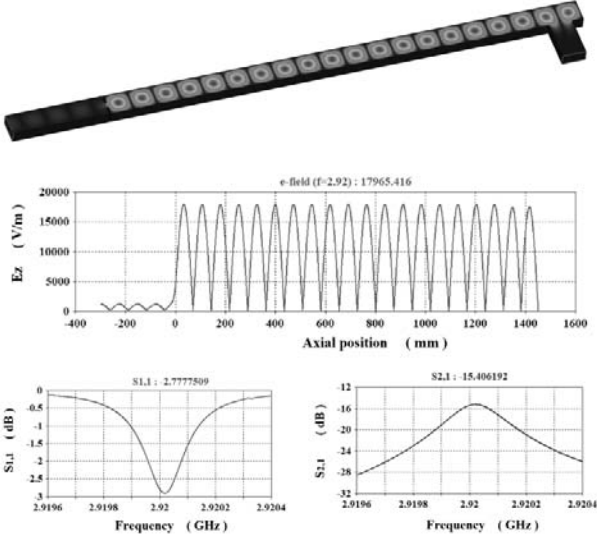


Fig. 3. Simulation results of the traditional microwave pulse compression system for the rectangular $TE_{1,0,20}$ resonant mode at 2.920GHz.

III. PHYSICAL PERFORMANCE AND THEORETICAL ANALYSIS

Based on the simulation results in Fig.2, the physical property of the over-moded microwave pulse compression system can be analyzed in detail, and compared with that of the traditional physical model as shown in Fig.3.

Here, it is concerned chiefly with four physical quantities: the coupling coefficient of the coupling window (κ_0), the energy storage efficiency of the microwave pulse compression system (β_0), the travelling-wave power (P_{TW}^\pm) in the resonant cavity, and the power gain (G_0) of the compressed microwave pulse. They are defined by the following set of equations, respectively[16-17].

$$\kappa_0 = 1.00 - |S_{1,1}|^2. \quad (1)$$

$$\beta_0 = 1.00 - |S_{1,1}|^2 - |S_{2,1}|^2. \quad (2)$$

$$P_{TW}^\pm = \frac{ab}{4Z_{TE10}} \times \left(\frac{E_z}{2}\right)^2 = \frac{ab}{4 \times 120\pi} \sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \times \left(\frac{E_z}{2}\right)^2 \quad (3)$$

$$G_0 = \frac{P_{TW}^\pm}{P_{in}}. \quad (4)$$

Where, E_z is the electric field component vertical to the wide side rather than the total electric field intensity; $\lambda_0=102.67\text{mm}$ and $\lambda_c=144.28\text{mm}$ for the rectangular $TE_{1,0,20}$ mode at 2.920GHz; $a \times b=72.14\text{mm} \times 34.04\text{mm}$ for the traditional physical model; $a \times b=72.14\text{mm} \times 68.08\text{mm}$ for the over-moded physical model; and input port and output port are set to be No.1 and No.2 respectively. The calculation results are listed in Table 1 for the rectangular $TE_{1,0,20}$ resonant mode at 2.920GHz in S-band.

TABLE I

RESULTS OF NUMERICAL SIMULATION AND THEORETICAL ANALYSIS FOR THE OVER-MODED MICROWAVE PULSE COMPRESSION SYSTEM AT 2.920GHz FOR THE RECTANGULAR $TE_{1,0,20}$ RESONANT MODE.

	L_0 (mm)	L_1 (mm)	$S_{1,1}$ (dB)	$S_{2,1}$ (dB)
Over-moded System	1452.90	69.40	-2.7778	-15.4062
Traditional System	1451.90	69.60	-4.7747	-34.8761
Re. Inc. Rate				
	E_z (V/m)	Q_0	β_0 (%)	G_0 (%)
Over-moded System	15645.54	2.7792×10^4	88.91	280.04:1.00
Traditional System	17965.40	1.8511×10^4	72.09	184.41:1.00
Re. Inc. Rate	-12.91%	+50.14%	+23.33	+51.85%

From the Table 1, it was shown that the power gain of the over-moded microwave pulse compression system has reached up to $G_0=280.04:1.00$ at 2.920GHz successfully for the rectangular $TE_{1,0,20}$ resonant mode. Relative to the 184.41:1.00 power gain of the traditional physical model for the same resonant mode at the same frequency, the power gain of the over-moded system has increase by +51.86%. It indicates that the over-moded microwave pulse compression system proposed in this paper has an excellent physical performance, just as the higher quality factor (Q_0) and higher energy storage efficiency (β_0) of the over-moded system, as shown in Table 1;

From the Table 1, it was also shown that the intensity of the standing-wave electric field has decreased by 12.91% relative to that of the traditional physical model. It implies that the over-moded system have a high power capacity than that of the traditional physical model. The relative increase of the power capacity is equal to the that of power gain, +51.85%. Thus, Based on the excellent physical property of high power gain and high power capacity, it is really possible to generate a output pulse with 28.0GW peak power with an input pulse with 100.0MW peak power in a chamber with N_2 -pressure of 100.0atm (10.00MPa) in experiment rather than in theory today, because we have had the advanced technology to generate UWB EMP with GW peak power in 150atm system. Here, 28GW corresponds to 2.21MV/cm ultra-high electric field intensity of the standing-wave in the resonant cavity at 2.920GHz. Because 10.00~15.00MPa N_2 -pressure can prevent from the discharge-induced by so high standing-wave intensity in the resonant cavity.

From the Table 1, it was also found that the optimal values of the resonant cavity length and the output window position is far different from the theoretic values of the idea model ($L_0=1461.36\text{mm}$ and $L_1=73.07\text{mm}$), whether for the new over-moded physical model (in Fig.2) or traditional physical model (in Fig.3). It is the existences of the coupling window and output waveguide in the actually physical system that induce the difference. In addition, the values of L_0 and L_1 for above two systems are also different from each other. This is because the system dimension is different from each other;

From the Table 1, the affections of deviations of the resonant cavity length and the output waveguide position on

the physical property of the high-gain over-moded physical model do not included. In order to examine qualitatively and calculate quantitatively the affection of the L_0 and L_1 to the β_0 , E_z and G_0 , two special cases are investigated: (1) L_1 deviates from the optimal value while L_0 keep the optimal value; (2) or vice versa. The calculation results are shown in Fig.4. It was found that, from Fig.4, if the position deviation of the output waveguide is $\pm 0.70\text{mm}$, the power gain of the system will decrease by 28.17% to 29.67%; If the length deviation of the resonant cavity is only $\pm 0.10\text{mm}$ rather than $\pm 0.70\text{mm}$, the power gain of the over-moded system will decrease by 61.45% to 67.17%. That indicate that these deviations will have a seriously affection to the physical property of the microwave pulse compression system and will result in an unimaginable consequences: small power gain;

From the Fig.4a, we can also see that when the system approaches to the optimal resonant state, β_0 , E_z and G_0 move toward the maximum values; But, in Fig.4b, the maximum power gain does not correspond to the maximum energy storage efficiency. That is an unexpected and unknown new phenomena. It is necessary to study the physical mechanism in future.

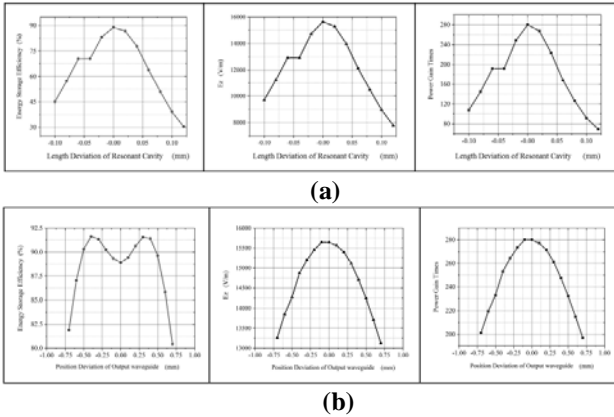


Fig. 4. Affection of deviation of L_0 or L_1 from the optimal value to β_0 , E_z and G_0 . (a) for L_0 ; (b) for L_1 .

IV. CONCLUSION

From the simulation results, calculation results and the theoretic analysis results, we can get the following conclusion to the high-gain over-moded microwave pulse compression system.

The over-moded microwave pulse compression system has an excellent physical property in the optimal resonant state: the power gain is as high as 280.04:1.00 for the rectangular $TE_{1,0,20}$ resonant mode at 2.920GHz in S-band. Relative to the traditional physical model, the power gain has increased by 51.86%.

There are a set of physical parameters values corresponding to the optimal resonant state of the over-moded microwave pulse compression system: The size of the coupling window is 19.80mm \times 34.04mm \times 3.00mm; The size of the over-moded

resonant cavity is 72.14mm \times 68.08mm \times 1452.90mm; The cross-sections of the output waveguide and input waveguide are is 72.14mm \times 34.04mm and 72.14mm \times 68.08mm. And $L_0=1452.90\text{mm}$, $L_1=69.40\text{mm}$ at 2.920GHz for the rectangular $TE_{1,0,20}$ resonant mode.

The power gain of the over-moded microwave pulse compression system is very sensitive to the deviations of the resonant cavity length and the output waveguide position from the optimal values. $\pm 0.1\text{mm}$ length deviation of the resonant cavity will result in the decrease of the power gain by 61.45% to 67.17%; And 28.17% to 29.67% decrease of the power gain for the $\pm 0.70\text{mm}$ position deviation of the output waveguide. This conclusion has very important application value to the experimental study and theoretical research, whether in S-band or in X, Ku and Ka bands;

This high-gain over-moded technology can be transplanted to X-and, Ku-band and Ka-band from S-band to keep a high power gain in these bands because of the universalities of the over-moded technology and physical principle.

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REFERENCES

- [1] M. Mangano, P. Azzi, M. D'Onofrio, and M. McCullough, "Physics at its limits", *CERN Courier*, vol.57,no.4, pp.34-40, May 2017.
- [2] E. Gibney, "China plans super collider", *Nature*, vol.511, pp.394-395, 24 July, 2014.
- [3] J. Ellis and I. Wilson, "New physics with the compact linear collider", *Nature*, vol. 409, pp.431-435, 18 Jan., 2001.
- [4] M. Benedikt, A. Blondel, P. Janot et al., "Future circular colliders succeeding the LHC", *Nature Physics*, vol.16, pp.402-407, 2020.
- [5] M. Franz, J. Wand, V. Dolgashev, and S. Tantawi, "Compact RF polarizer and its application compression system", *Phys. Rev. Accel. Beams*, vol.12, 2016, Art. no. 062002, doi: 10.1103/PhysAccelBeams.19.062002.
- [6] A. L. Vikharev, O. A. Ivanov, A. M. Gorbachev, M. A. Lobaev, V. A. Isaev, S. G. Tantawi, J. R. Lewandowski, and J. L. Hirshfield, "X-band active-passive RF pulse compression with plasma switch", *Phys. Rev. Accel. Beams*, vol.14, 2011 Art. no. 121302, doi: 10.1103/PhysAccelBeams.12.121302
- [7] Y. Jiang, H. Zha, P. Wang, J. Shi, H. Chen, W. L. Miller, and L. Syratchev, "Demonstration of a cavity-based pulse compression system for pulse shape correction", *Phys. Rev. Accel. Beams*, vol.22, 2019,, Art. no. 082001, doi: 10.1103/PhysAccelBeams.22.082001.
- [8] J. W. Wang. and, S. G. Tantawi, X. Chen M. Franz, P. Krejcik, G. Bowden, S. Condamoor, Y. T. Ding, V. Golgashev, J. Eichner, A. Haase, J. R. Lewandowski, and L. L. Xiao, "Development for a super-compact X-band pulse compression system and its application at SLAC", *Phys. Rev. Accel. Beams*, vol.20, 2017, Art. no. 110401, doi: 10.1103/PhysAccelBeams.20.110401.
- [9] O. A. Ivanov, M. A. Lobaev, A. L. Vikharev, A. M. Gorbachev, V. A. Isaev, J. L. Hirshfield, S. H. Gold, and A. K. Kinkead, "Active microwave pulse compressor using an electron-beams switch", *Phys. Rev. Lett.* Vol., Vol.110, 15 March, 2013, Art. no. 115002, doi: 10.1103/PhysRevLett.110.115002.
- [10] O. A. Ivanov, V. A. Isaev, M. A. Lobaev, A. L. Vikharev, and J. L. Hirshfield, "A resonance switch employing an explosive-emission cathode for high-power rf pulse compressor", *Appl. Phys. Lett.*, vol. 97, 2010, , Art. no. 115002, doi: 10.1103/1.3466911
- [11] A. L. Vikharev, A. M. Gorbachev, Q. A. Ivanov, V. A. Isaev, S. V. Kuzikov, M. A. Lobaev, J. L. Hirshfield, S. H. Gold, and A. K. Kinkead,

- “High power active X-band pulse compression using plasma switches”, *Phys. Rev. ST Accel. Beams*, Vol.12 , 2009, Art. no. 062003, doi: 10.1103/PhysRevSTAB.12.062003.
- [12] S. N. Artemenko, V. S. Igumov, A. S. Shlapakovskiy, and Y. G. Yushkov, “Compact active S-band microwave compressors for producing rectangular pulses of up to 100ns”, *IEEE Trans. Microw. Theory Techn.*, vol.67, no.2, pp. 597-605, Feb. 2019, doi: 10.1109/TMTT.2018.2886850.
- [13] Z. Lin, T. Jiang, S. Huang, Z. Xue, Z. Gao, R. Wang, F. Zeng, L. Li, Y. Huang, Z. Yang, A. Wu, R. Zhang, Y. Li, M. Xu, Z. Zhang, and Y. Zhang, “Development of a movable standing-wave resonant test system for fundamental power coupler with an extraordinary power gain”, *Phys. Rev. Accel. Beams*, vol. 25, 2022, Art. no. 012001, doi: 10.1103/PhysAccel Beams.25.012001.
- [14] S. P. Savaidis, Z. C. Ioannidis, S. A. Mitilineos, and N. A. Stathopoulos, “Design waveguide microwave pulse compressor using equivalent circuits” *IEEE Trans. Microw. Theory Techn.*, vol.63, no.1, pp.125-134, Jan. 2015, doi:10.1109/TMTT.2014.2374598.
- [15] P. J. Hackney, D. J. Mellor, G. D. Stimson, AND J. R. G. twisleton, “High power short pulse generation at s-band using a waveguide cavity with laser initiated discharge”, *Electronics Lett.*, vol.31, no.15, pp. 1263-1264, July 1995
- [16] E. G. Farr, L. H. Bowen, W. D. Prather, and C. E. Baum, “Microwave pulse compression experiments at low and high power”, *Circuit and Electromagnetic System Design Notes*, Note 63, pp.1-30, 2010.
- [17] A. D. Andreev, E. G. Farr, and E. Schamiloglu, “A simplified theory of microwave pulse compression”, *Circuit and Electromagnetic System Design Notes*, Note57, pp. 1-11, 2008.
- [18] S. G. Tantawi and C. D. Nantista, “Active and passive RF components for high-power system”, *SLAC-PUB-9499*, pp.1-17, 2002.
- [19] S. G. Tantawi, “Overmoded waveguide component for high-power RF”, *SLAC-PUB-10218*, pp.1-8, 2003.