Backward-Wave Oscillator with Distributed Power Extraction Operating at an Exceptional Point of Degeneracy

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Abstract: *We propose a new and efficient degenerate synchronous regime for backward wave oscillators (BWO) based on an exceptional point of degeneracy (EPD) in the RF-electron beam interactive system. Compared to conventional BWOs, we introduce distributed power extraction all the way along the BWO structure. The EPD is obtained in the interactive RF-beam system by the simultaneous presence of distributed gain (due to the electron beam) and power extraction. Current PIC simulation results show that at a guiding magnetic field of 2.6 T, electron beam of 600 kV and 1740 A, an output power of 0.5 GW is extracted with power conversion efficiency of 47% and oscillation frequency of 9.7 GHz. This paper shows the feasibility of this new concept, and performance could be further improved.*

Keywords: Exceptional point of degeneracy (EPD); Slow wave structures (SWS); Backward wave oscillators (BWO); High power microwave (HPM).

Introduction

Exceptional points of degeneracy (EPDs) are points in parameter space of a system at which two or more eigenmodes coalesce in their eigenvalues (wavenumbers) and eigenvectors (polarization states). Since the characterizing feature of an exceptional point is the strong degeneracy of at least two eigenmodes, as implied in [1], we stress the importance to refer to it as "degeneracy". Despite most of the published work on EPDs is related to PT symmetry [2] the occurrence of an EPD actually does not require a system to satisfy PT symmetry. The system considered here indeed does not satisfy that condition, involving two completed different media that support waves, a plasma and a waveguide for electromagnetic waves, but still requires their interaction and the simultaneous presence of gain and loss. The gain represents the energy extracted from the electron beam and delivered to the guided electromagnetic mode, whereas "loss" represents the distributed power extraction (DPE) along the waveguide [3], [4] and not mere dissipation.

Backward-wave oscillators (BWOs) are high power sources where the power is transferred from a very energetic electron beam to a coupled electromagnetic mode. The extracted power in a conventional BWO is taken at one end of the slow wave structure (SWS). One challenging issue in BWOs is the limitation in power generation level. Indeed, conventional BWOs exhibit small starting beam current (to induce sustained oscillations) and limited power efficiency without reaching very high output power levels. Several techniques where proposed in literature to enhance the power conversion efficiency of BWOs by optimizing the SWS and its termination. In [5], a resonant reflector was used to enhance the efficiency to about 30%. A two-sectional SWS was also proposed to enhance the power efficiency in [6].

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In this paper we propose a new regime of operation of BWOs based on an EPD that has not been explored yet in literature, to enhance the efficiency and power generation level. The use of EPD for this new regime of operation allows to have a fully "degenerate synchronization" which means that two complex modes of the RF-electron beam interactive system do not share just the wavenumber, but they rather coalesce in both their wavenumbers and polarization states, i.e., they are identical in the RF-beam interactive regime.

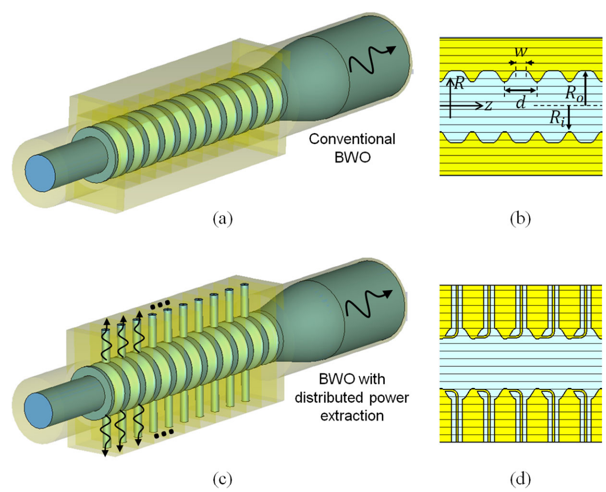

Fig. 1. Backward wave oscillator (BWO): (a) conventional BWO where the power is extracted from the waveguide end; (c) EPD-BWO where the power is extracted in a distributed fashion to satisfy the EPD condition [3], [4]. The power is extracted using distributed wire loops (as an example) that are connected to coaxial waveguides as in Ch. 10 in [7]; (b) and (d) are longitudinal cross-sections for SWSs used in both BWOs.

Principle and Results

We first consider the SWS of a conventional BWO, shown in Fig. 1(a,b) , that does not have distributed power extraction. The SWS has azimuthal symmetry and has inner and outer radii of $R_i = 14$ mm and $R_o = 16.5$ mm, respectively. The SWS has period $d = 15$ mm. The surface of SWS along one period is described by a flat surface $R(z) = R_o$ for $0 \le z < w$, where $w = 5$ mm, and sinusoidal corrugated surfaces $R(z) = 0.5(R_o + R_i) + 0.5(R_o - R_i)\cos(2\pi(z-w)/(d-w))$ for the rest of the period, $w \le z < d$.

Based on our work in [3], [4], we found that a second order EPD in a system made of an electromagnetic wave interacting with an electron beam's charge wave is obtained when the per-unit length and impedance and admittance representing the transmission line circuit model of the EM mode in the SWS have some real part, i.e., losses. “Losses” (from the SWS point of view) are not dissipative but they represent distributed power extraction along the SWS as in Fig. 1(d). We add a wire loop in each unit cell, that couples the magnetic field in the azimuthal direction and converts it to current that excite the coaxial waveguide as in Ch. 10 in [7].

Figure 2 shows a comparison between the dispersion relation of RF modes in two “cold” SWSs: one used in the conventional BWO in Fig. 1(b), and one used in the BWO with DPE in Fig. 1(d). The dispersion curves show only the RF mode that is TM-like, i.e., the one with an axial electric field component. The dispersion curves show that the RF mode in the SWS with DPE is a backward wave that has a propagation constant with non-zero imaginary part (this is a cold SWS) at the frequency where the interactions with the electron beam would occur, i.e., at the point where the EM wave phase speed is synchronized to the speed of electrons. This means that the structure in Fig. 1(d) is suitable for our design of an EPD-BWO and can satisfy the EPD condition [3], [4]. The dispersion of the complex-wavenumber modes in the interactive RF-electron beam system has been shown in [3], [4] using the Pierce model revealing the occurrence of an EPD.

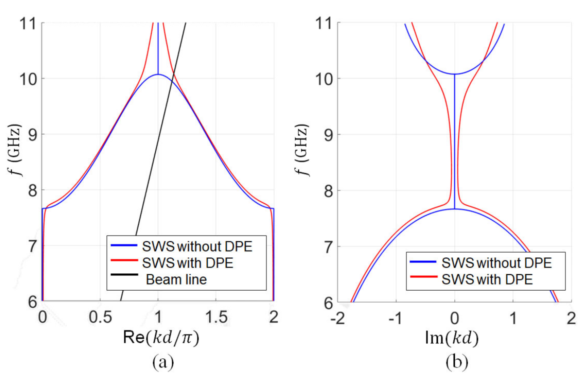

Fig. 2. Dispersion of guided modes in the“cold” SWSs in Fig. 1(b) and 1(d), without (blue curve) and with (red curve) distributed power extraction (DPE). (a) Real part and (b) imaginary part of the complex wavenumber. The imaginary part of wavenumber shows that the SWS in Fig. 1(b) exhibits non-zero imaginary part because of the distributed power extraction. The hot SWS with DPE is designed to

Simulations based on the particle in cell (PIC), implemented in CST, use an annular beam with inner and outer radii $R_{ib} = 9$ mm and R_{ob} = =10.3 mm, respectively. We use a relativistic DC electron beam with DC voltage of 600 kV and guiding magnetic field of 2.6 T. We compare the power efficiency (output power over beam power) of conventional BWO and EPD-BWO in Fig. 3 for different values of the electron-beam DC current. The figure shows that the EPD-BWO has higher efficiency at higher level of output power compared to a conventional BWO with same dimensions. The Figure shows that the EPD-BWO has a maximum efficiency of about 47% at about 0.5 GW output power (the sum of the power from each output in Fig. 1(b)). However, the conventional BWO has maximum efficiency of about 33% at output power level of about 0.27 GW. It is also important to point out that EPD-BWO has higher threshold beam current to start oscillations compared to the conventional one which is consistent with the theoretical results in [3], [4]. These PIC results are intended to show the first ever feasibility of the EPD-BWO concept and some possible advantages and should not be considered as an actual design.

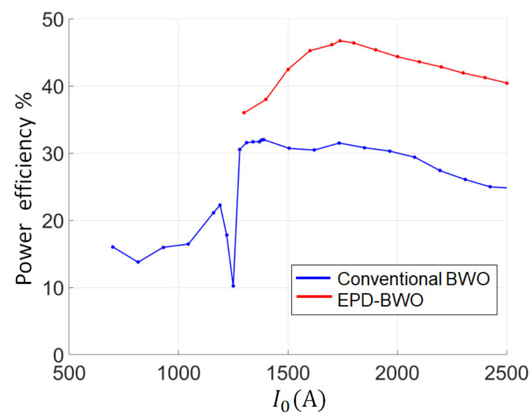

Fig. 3. Comparison between the efficiency of a conventional BWO and an EPD-BWO. The EPD-BWO shows improved efficiency at higher level of power generation compared to the conventional BWO.

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