Theory of an optical parametric oscillator with resonant pump and signal

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Received March 11, 1999; revised manuscript received June 7, 1999

We derive the properties of a pump-resonant singly resonant optical parametric oscillator for which the pump and one of the parametrically generated waves share a common cavity. Wave-vector mismatch and focusing effects are taken into account. We calculate the oscillation threshold and its dependence on emission wavelengths as the result of mode shape changes. The conversion efficiencies for signal and idler waves are calculated. It is shown that one can maximize the conversion efficiencies by optimizing mirror transmissivities. The interference effects that occur in a standing-wave geometry and the mode content of the nonresonant wave are also analyzed. © 1999 Optical Society of America [S0740-3224(99)02509-6]

OCIS codes: 190.2620, 190.4410, 190.4970.

1. INTRODUCTION

Recently, continuous-wave optical parametric oscillators (OPO's) have reached a stage of development at which they can be used for high-resolution spectroscopy, and first demonstrations have been made.[1–5]

In those studies several kinds of OPO were used. Among these, the singly resonant OPO with a resonant pump is particularly interesting because single-frequency, mode-hop-free oscillation can be combined with a large emission range and a modest threshold.[6] Resonating the pump is responsible for the first two features, with the additional possibility of obtaining signal and idler waves with narrow linewidth and low frequency drift if a pump source with the same features is used. A linewidth below 160 kHz (Ref. 7) and a frequency drift below 30 MHz/h (Ref. 5) were demonstrated. The large emission range [1.45–4.0 μm (Ref. 6)] is possible because the OPO resonator needs to have low loss only over the relatively limited signal wave spectral range, for which high-reflectivity dielectric multilayer coatings are feasible.

The pump-resonant (PR) SRO was first considered conceptually more than 30 years ago[8] and was experimentally realized by Robertson *et al.*[9] following the first continuous-wave non-PR SRO.[10] In view of the recent developments that have turned this type of device into a useful spectroscopic tool, it appears timely to present a detailed theory of the PR SRO that may serve as a guide to the design of concrete devices.[11]

Our goal in this paper is to give simple expressions for the nonlinearity (in SI units) and of the threshold of a general PR SRO. In practice, both ring and standing-wave resonators can be used; thus the thresholds for both configurations are given. In addition, the conversion efficiencies to both signal and idler above threshold are of central interest. For other nonlinear devices, such as harmonic generators and doubly resonant OPO's, the optimization of their conversion efficiencies by appropriate choice of cavity mirror transmission(s) has been discussed in the literature. We show here that such an optimization is also possible and useful for a PR SRO.

Central to the present treatment is that TEM$_{00}$ signal and pump modes with arbitrary (but equal) focusing are considered; i.e., the cavity that defines these two modes can have mirrors with arbitrary radii of curvature (within the stability region). This implies that one has to treat the idler wave in a general way by expanding it in TEM$_{mn}$ modes. The optimum focusing that leads to maximum nonlinearity and lowest threshold is determined. Also, it is of interest to evaluate the TEM$_{00}$ mode content of the idler by finding the TEM$_{00}$ mode that best fits the idler wave.

In our treatment we make connections with related research, in particular with that of Guha *et al.*[12] on the threshold of the non-PR SRO with arbitrary focusing and with the treatment by Yang *et al.*[13] of the plane-wave standing-wave SRO with reflected pump and idler.

We start with the introduction of the device to be considered and the propagation equations for the fields. Their solution is given in Section 3 to second order in the nonlinearity and for small wave-vector mismatch. Section 4 introduces the resonance conditions, i.e., expressions for pump and signal frequencies and amplitudes when the oscillator is in the steady state. The central results of this paper are contained in Section 5, where expressions for the threshold and output powers are given. A cavity configuration of practical relevance is the standing-wave cavity, and Section 6 is devoted to its discussion. Section 7 presents a discussion of ways in which threshold and conversion efficiencies can be optimized by proper choice of cavity mirror transmissivities. Explicit calculations of the nonlinearity that determines the threshold and of mode content of the nonresonant wave are presented in Sections 8 and 9.

2. SYSTEM

Figure 1 shows one of the types of device considered in this paper. It is a monolithic ring resonator; the round-trip path length for pump and signal waves is $L_{\rm rt}$. The