UNIVERSITI PUTRA MALAYSIA

NONLINEAR FIBER OPTICAL PARAMETRIC AMPLIFIERS AND LASERS WITH IDLER REMOVAL FILTER

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By

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To my beloved parents

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Nonlinear phenomena in optical fiber have been seen detrimental to the performance of fiber optical communication systems; however, in many niche areas optical fiber nonlinear properties are very much desired. Nonlinear Four-wave mixing (FWM) process in optical fiber is generally referred as fiber optical parametric process, for the reason that fiber parameters are deliberately designed to enhance the efficiency of FWM. Among the most important parameters that define the parametric process are the chromatic dispersion profile (related to second-order dispersion), dispersion slope (related to forth-order dispersion), zero-dispersion wavelength and fiber nonlinear coefficient. Silica-based highly nonlinear fibers (HNLFs) are the fiber medium of choice in most parametric experiments mainly because of its excellent fiber attenuation performance and low splice-loss when connected to standard single mode fiber (SMF). Even though HNLF and SMF are both silica-host optical fibers, they are nevertheless incompatible in several fiber characteristics, in which most prominently is their fiber dispersion profile. Incorporating HNLF to an SMF-based system would lead to a phenomenon known as wavelength-dependent gain modulation, where parametric gain ripples exist across the spectrum, with peak and notch gain difference as much as 20 dB. The origin of the gain ripples is investigated theoretically and experimentally. Investigation indicates that by suppressing the idler power by 60 dB, the gain ripples can be smoothened and thus restore the original gain shape of the parametric devices, but with tolerable gain loss around 6 dB. The idler removal filters (IRFs) then become the key enabling device for fiber optical parametric devices with two-segment design as well as double-pass pump configuration. Properly designed IRFs are proven to successfully smoothen gain ripples that exist in a two-segment fiber optical parametric amplifier (FOPA). Experiments also show that a parametric gain improvement of 10 dB is achieved in FOPA with double-pass pump configuration at 1.05 W pump power, and gain slope of 47.5 dB/W has been achieved. The power penalty at bit error rate 10^{-6} is found to be within 5 dB for this double-pass FOPA design, which successfully addresses the practicability issue of this special kind of FOPA design. The IRF is extended in fiber optical parametric oscillator (FOPO) to realize double-pass design FOPO. Besides

the significant laser tuning wavelength improvement (72 nm @ 0.45 W, limited by wavelength range of tunable bandpass filter), the double-pass pump FOPO achieves as high as 51% threshold power improvement as compared to the conventional configuration, in addition maintaining laser peak stability within 2 dB.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGUAT PARAMETRIK GENTIAN OPTIK DAN LASER TIDAK LINEAR DENGAN TURAS PENAPISAN IDLER

Oleh

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Dalam kebanyakan masa, fenomena tidak linear dalam gentian optik dilihat sebagai sesuatu yang akan menjejaskan prestasi sistem komunikasi optik. Tetapi dalam keadaan tertentu, fenomena tidak linear gentian adalah dikehendaki. Pergaulan empat gelombang tidak linear (‘*Four-wave Mixing’*, FWM) dikenali sebagai proses parametrik, disebabkan pelbagai penyesuaian teliti atas parameter gentian boleh menjana proses tersebut dengan berkesan. Antara parameter-parameter penentu yang penting untuk menjanakan proses parametrik efektif termasuklah penyerakan kromat gentian, kecerunan penyerakan, jarak gelombang penyerakan sifar dan pekali tidak linear gentian. Gentian silika amat tidak linear (‘*highly nonlinear fiber*’, HNLF) adalah medium gentian popular yang digunakan dalam kebanyakan eksperimen disebabkan ia mempunyai ciri-ciri seperti kehilangan kuasa minimum sama ada ketika penyaluran ataupun cantuman dengan gentian mod tunggal (‘*single mode fiber*’, SMF). Walaupun HNLF dan SMF adalah gentian silika, tetapi mereka mempunyai parameter-parameter gentian yang amat berbeza, antara percanggahan yang utama adalah kepadanan dari segi penyerakan kromat. Akibatnya, pemodulatan gandaan bergantung dengan jarak gelombang akan berlaku di mana riak gandaan parametrik dengan nisbah setinggi 20 dB akan wujud di seluruh spektrum. Tesis ini menyiasat asal-usul riak gandaan tersebut secara teori dan experimen. Siasatan menunjukan pengecilan kuasa idler sebanyak 60 dB dapat menghapuskan riak gandaan tetapi akan mengakibatkan pegecilan gandaan sebanyak 6 dB yang dianggap munasabah. Dengan rekacipta turas penapisan idler (IRF) yang bersesuaian, riak gandaan dalam penguat gentian optik parametrik jenis dua segmen dapat ditangani.. Keputusan eksperimen-eksperimen menyatakan dengan konfigurasi lintas-kembar, peningkatan gandaan sebanyak 10 dB dicapai oleh penguat isyarat parametric dengan hanya 1.05 W kuasa pam, dan 47.5 dB/W kecerunan penguatan. Pinalti kuasa pada kadar ralat bit 10^{-6} adalah kurang daripada 5 dB dan ini berjaya menunjukkan praktikaliti rekacipta lintas-kembar penguat isyarat ini. Kegunaan IRF boleh dilanjutkan seterusnya dalam pengayun parametric dengan rekacipta lintas-kembar. Di samping penalaan jarak gelombang dapat dipanjangkan dengan ketara (sebanyak 72 nm @ 0.45 W, dihadkan oleh jalur lebar penala laluan gelombang), sebanyak 51% penurunan laser ambang dapat dicapai oleh pengayun parametric dengan rekecipta

lintas-kembar berbanding dengan rekacipta konvensional, tambahan atas pengekalan kestabilan laser dalam lingkungan 2 dB.

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TABLE OF CONTENTS