COMB GENERATING OPTICAL CAVITY THAT INCLUDES AN OPTICAL AMPLIFIER AND AN OPTICAL MODULATOR

CROSS REFERENCE TO RELATED APPLICATION

Provisional patent application Ser. No. 60/072,243, filed Jan. 23, 1998, entitled OPTICAL FREQUENCY SHIFTER WITH OPTICAL GAIN by John. L. Hall, Jun Ye, and Long-Sheng Ma.

The United States of America as represented by the Secretary of Commerce, National Institute of Standards and Technology, may have rights under this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the field of optical frequency generators, and more specifically, to the generation of optical frequency combs.

2. Description of the Related Art

An Electro-Optic Modulator (EOM), when driven by an appropriate single Radio Frequency (RF) electromagnetic field, produces optical frequency light sidebands on an original single frequency light beam that traverses the EOM. The sidebands are equally spaced about the input beam. The spectral extent of the sidebands can be increased by recirculating the modulated light beam through the EOM, to thereby iteratively produce additional light sidebands on each daughter light beam that was generated by a previous interaction. In this way, an optical comb is built up, the spectral extension of which is limited by optical transmission losses, phase mismatching error associated with synchronization or length errors, and wavelength "breadth" induced phase dispersion of the EOM and its mirrors. (See, for example, "A Highly Accurate Frequency Counting System for 1.5 Micro Meter Wavelength Semiconductor Lasers', PROCEEDINGS OF THE SPIE, Vol. 1837, 16–18 Nov. 1992, pp. 205–215, by M. Kurogi, K. Nakagawa, and M. Ohtsu, and "Optical Frequency Comb Generator", *IEEE J. Quant. Electr.*, Vol. 29, Oct. 1993 pp. 2693–2701 (1993), by M. Kurogi, K. Nakagawa, and M. Ohtsu.

FIG. **1** shows the output of such a prior comb generating cavity **60** that operates to generate an optical frequency comb **61** having sideband portions **62** and **63** that are centered upon the frequency **64** of an input laser **65**. Increasing frequencies within OFC **61** are shown by increasing values along the X axis, and the relative power in each comb frequency is shown on the logarithmic Y axis, the power of frequency **64** being the largest amplitude

In accordance with an aspect of the present invention, comb-generating cavity **60** includes an optical amplifier or optical parametric amplifier, and the utility of optical comb **61** is enhanced by the use of a resonant and tunable bandpass filter optical cavity that operates as a direct output coupler for comb-generating cavity **60**. This output coupler operates to increase the strength of a selected comb frequency component by several orders of magnitude.

A publication by John. L. Hall ("Frequency stabilized lasers—a parochial review", *Proceedings Reprint, SPIE*, Vol. 1837, 16–18 November 1992, pgs. 2–15, at section 5.4.2 on page 12) recognizes Kurogi, Nakagawa and Ohtsu as providing a microwave modulator that is enclosed in a low-loss cavity, wherein a sideband that is produced on the first transit is used as the source for a second sideband, and the second for a third, etc., whereby a spectral width of about + and −4 THz is provided, made up of individual lines spaced by the 5.6 GHz frequency. Hall then suggests "recycling" the light reflected back toward the source from the entrance mirror. It is also suggested that if this recycling cavity is short enough, the recycling cavity could be resonance free until one reaches the desired high order sideband, perhaps some THz away. The modulation power in this line would be coupled back toward the source, and could be separated with a Faraday isolator system. It is suggested that such schemes may make it feasible to transfer the stability of one optical source in a phase coherent manner to another source located an appreciable frequency interval away.

An article entitled "A Coupled Cavity Monolithic Optical Frequency Comb Generator" by M. Kourogi, T. Enaeni and M . Ohtsu in IEEE PHOTONICS TECHNOLOGY LETTERS, Vol. 8, No. 12, December 1996, describes an optical frequency comb generator (or a Fabry Perot electro-optic modulator) that generates ultra short optical pulses, and high order sidebands from a single mode laser input. A high efficiency electro-optic phase modulator is installed in a high finesse optical cavity, and driven with an integer multiple of the cavity free spectral range.

Two types of optical frequency comb generators are discussed, each having an external coupled cavity, one to achieve efficient comb generation, and the other to provide a frequency shifter.

In the FIG. **1***a* embodiment of this publication, a mirror **M3** was mounted on a PZT transducer, and placed in front of a mirror **M1** to form a coupled cavity, and the coupled cavity was adjusted to the laser frequency. As a result, the incident light is transmitted by the coupled cavity, while the coupled cavity becomes highly reflective for the sidebands generated by the comb generator.

To allow the selection of extracted sidebands, the above-described coupled cavity of FIG. **1***a* was removed from the input port of the comb generator, and as shown in FIG. **1***b* of this publication, and PZT mounted mirror **M3** was installed at the output port. By adjusting the bias voltage at the PZT on which mirror **M3** was mounted, an appropriate set of sidebands may be selected.

This publication also suggests that if two stable coupled cavities are installed at the input and the output port of the comb generator, the power of the selected sideband may be increased, in which case, the comb generator will become a highly efficiency frequency shifter for a wide frequency range.

An article entitled "Efficient optical frequency comb generator" by A. S. Bell, G. M. McFarlane, E. Riis and A. I. Ferguson, OPTICS LETTERS, Vol. 20. No. 12, Jun. 15, 1995, also describes an arrangement having two cavities that are locked to a laser carrier frequency. This publication describes how an unknown laser frequency can be measured with respect to a well-known standard frequency. This publication also describes how large frequency differences can be determined, based on a few rf measurements. A comb of equally-spaced modes is produced from a single laser carrier frequency. An electro-optic modulator superimposes a microwave frequency onto the carrier frequency, thus producing a comb of nodes with spacing of exactly the microwave frequency. The electro-optic modulator is placed into a three mirror dogleg cavity that is resonant to both the carrier frequency and the sidebands. A second cavity is used to ensure that most of the incident laser power is coupled into the optical cavity. To increase the coupling of the laser into the optical cavity, and hence increase the throughput of the comb generator, a PZT-mounted mirror **M1** is placed