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FEASIBILITY OF AN OPTICAL FREQUENCY MODULATION SYSTEM FOR FREE-SPACE OPTICAL COMMUNICATIONS

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We consider a free-space communication system based on optical frequency modulation (FM), where the information is encoded by a time-variable wavelength. As is well known, broadband FM systems use a transmission bandwidth that is larger than the signal's information bandwidth, thus enabling an enhancement of the signal-to-noise ratio (SNR) and hence the effective information rate per unit transmitter power. Because of the atmospheric conditions, any optical free-space communication system, contemplated at a terrestrial level, must operate at mid-infrared wavelengths in the range λ = 2.5−2.8 μm. Development of rapidly tunable single-frequency lasers in this wavelength range is quite feasible, based on the current experience with tunable telecom lasers at 1.5 μm. Nevertheless, there is no currently available optical FM system. The main difficulty is associated not so much with the tunable optical sources, as with the implementation of a wavelength-discriminating receiver system that would take advantage of the enhanced SNR. In our view, the key enabling solution is optical superheterodyne with a local oscillator implemented as a tunable mid-infrared laser similar to that at the source. The intermediate frequency can be tuned to lie either in a frequency range directly accessible to *electronic* limiting amplifier and frequency discriminator or, in a multichannel system, to a second heterodyne in the terahertz range.

1. Introduction

As is well known from radio-electronics, wideband frequency-modulation (FM) systems offer a trade of the bandwidth excess for signal to noise ratio, thus relaxing the transmitter power requirement as compared to AM transmission. Energy efficiency is essential for satellite communications, sensor networks and mobile platforms. The FM advantage is proportional to the squared ratio $(\Delta F / f_S)^2$ of the range of frequency excursion ΔF to the signal bandwidth f_S, see, e.g., a recent discussion by Hayes[1]. Thus current direct broadcast satellite systems are made possible by using a microwave bandwidth $\Delta F = 28$ MHz to transmit each 3-MHz television channel, thus gaining nearly 20 dB in signal to noise ratio. The structure of a FM signal is illustrated in Fig. 1.

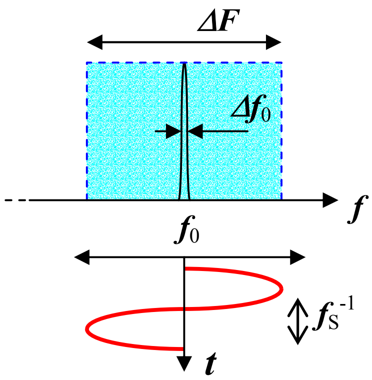

Fig. 1. Nomenclature of frequencies involved in a FM communication link.

f_0 center laser line (100 THz for $\lambda = 3\ \mu\text{m}$)

Δf_0 laser linewidth

ΔF frequency excursion

f_S signal bandwidth

To preserve the FM advantage, the signal bandwidth is limited by the inequality,

$$f_S << \Delta F << f_0 \,. \tag{1}$$

This should not be a serious limitation for optical FM in any wavelength range, since optical frequencies are far larger than any conceivable signal bandwidth. A more stringent condition limits the spectral width Δf_0 of the laser emission. Linewidth is not an issue in radio systems. Compared to such systems, any laser is a high-Q resonator in the sense of $\Delta f_0 << f_0$. However, as we shall argue below, the only practical receiving system that can be contemplated for optical FM should be based on optical heterodyne and since the linewidth is "inherited" in heterodyne detection, one must ensure it stays well below the tuning range, viz.

$$\Delta f_0 << \Delta F \,. \tag{2}$$

Condition (2) can be viewed as an optical analog of the so-called FM threshold.[1] This is certainly quite feasible with single-mode semiconductor lasers.

The wavelengths of interest for free space communications are determined by the background radiation as well as windows of atmospheric transparency. Figure 2 shows the background optical power received by a free-space detector at the terrestrial level. It is clear from Figure 2, that the implementation of terrestrial free-space communication links is almost certain to require mid-infrared wavelengths. The optimum combination of minimal background and high atmospheric transparency at the terrestrial level is in the range 2.5 – 2.75 μm. Development of mid-IR rapidly tunable diode lasers in this range is therefore the enabling technology for terrestrial free-space communications. On the other hand, for intersatellite communications, where thermal emission by atmospheric gases is minimal, the preferable range is near 10 µm.

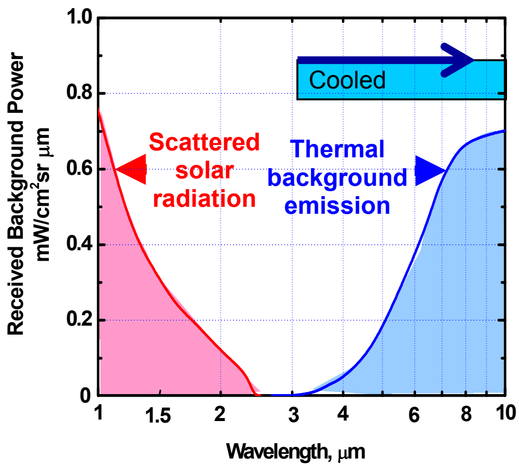

Fig. 2. Spectral dependence of the background optical power received by a terrestrial detector.

The intensity of scattered solar radiation decreases in accordance with Sun's surface temperature of approximately 6,000K. At the same time, we see increasing thermal emission by the atmospheric gases at 300K.

The shaded regions correspond to atmospheric absorption bands.

2. Tunable lasers

A tutorial review of tunable semiconductor lasers was given by Coldren *et al.*[2] A tunable "single-frequency" laser comprises a mode selection filter, most commonly a distributed feedback (DFB) grating, and means for adjusting some internal parameter that controls the lasing frequency. For our purposes, we should distinguish between "slow" and "fast" tuning mechanisms, where the speed is judged relative to modern communications bandwidth. We shall refer to as fast those tuning mechanisms that allow modulation of the emission wavelength at bandwidths in excess of 1 GHz. Slower tuning mechanisms are also very useful but for purposes other than optical FM communications, e.g., for sensor applications and for wavelength division multiplexing (WDM) communication systems. The basic tuning mechanisms in single frequency lasers, reviewed by Coldren *et al.*[2] and illustrated in Fig. 3, include the adjustments in the cavity length, e.g., by movable mirrors, and the mode selection, e.g., by variable index or grating angle. For unipolar (quantum cascade) lasers, one can use a DFB effect provided by the piezo-acoustic interaction with a propagating sound wave, whose wavelength is tunable by changing the sound frequency.[3] These are relatively slow tuning mechanisms suitable for spectroscopic sensors and coarse wavelength selection, but not for signal encoding. On the other hand, tuning the net cavity refractive index can be done electrically and very rapidly. Such electro-optic techniques have no frequency limitation within the context of modulation bandwidths provided by the transistor electronics.

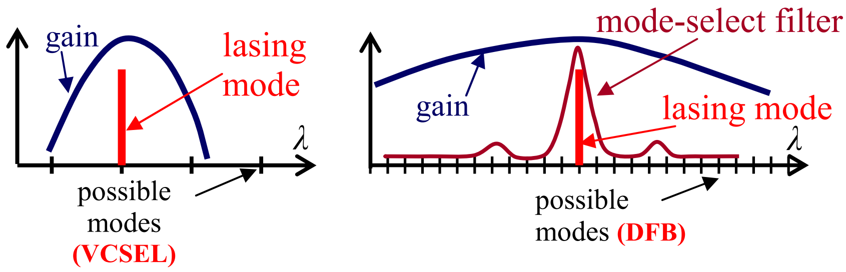

Fig. 3. Tunable single-mode lasers, vertical-cavity surface-emitting lasers (VCSEL) and distributed-feedback lasers (DFB).

Recently Suchalkin *et al.*[4] reported a tunable mid-infrared optical source ($\lambda \approx 2.75$ μm), based on a specially designed tunneling injection mechanism that provides fast-mode tunability. In this structiure, the effective refractive index can be tuned electrically by the variation of carrier concentration in the active layers *above threshold*. The resultant free-space wavelength variation is over 10 Å, giving a minimum frequency excursion $\Delta F \approx 30$ GHz and thus enabling a single-channel bandwidth f_S of at least 3 GHz. The same structure showed also a coarse wavelength tuning by electrical pumping current at the rate of about 72 meV·cm^2/kA and over a range of nearly 80 meV arising due to a linear Stark shift of energy levels in an asymmetric heterojunction. The combination of rapid smooth fine tuning with coarsely tunable "center" frequency in the mid-IR range is very attractive for optical FM applications.

3. Heterodyne detection

One of the key difficulties of optical FM is to implement a detection scheme that would preserve the signal-to-noise advantage, inherent in FM. Thus, it is hardly possible to use a direct optical wavelength discriminator, e.g., that based on a semiconductor fundamental absorption edge, see Fig. 4. The main problem is that the received FM signal would be inextricably mixed with amplitude variations. In electronics, the problem is solved by inserting prior to the frequency discriminator a limiting pre-amplifier that brings all received frequencies to the same level of amplitude. It is unclear whether or not there can be a viable optical analog of the limiting amplifier.

Another (less serious) problem with direct optical frequency discrimination arises due to the fact that the typical spectral response is a highly nonlinear function of wavelength, with non-zero response at the central frequency (shown in Fig. 4 by the dashed line). The non-zero response is an essential nonlinearity in the analog optical FM system. It brings about additional noise due to the SNR dependence on both the signal amplitude and polarity. This problem should be solvable, at least in the 10 µm wavelength range, by employing fast and efficient detectors based on the resonant photon-drag effect in quantum wells.[5-7] The problem of AM contamination, however, remains and it can be solved only by the introduction of a viable optical limiting amplifier.

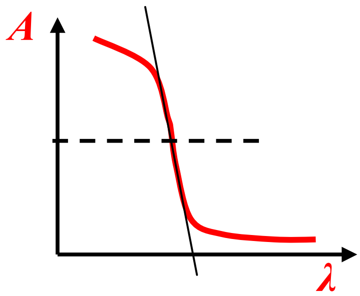

Fig. 4. Spectral response of a detector effecting direct optical frequency discrimination.

Electrical signal generated by an optical FM signal *λ(t)* is itself amplitude-modulated. Contamination by wavelength-dependent amplitude variations is inextricably mixed with the response *A(λ)*. This type of detector can only be used in conjunction with an optical limiting amplifier, a hypothetical device that would bring all the received wavelengths to the same level of optical amplitude.

The heterodyne detection scheme, discussed below, obviates this problem, since the downconverted signal at the intermediate frequency is still an FM signal and can be purified of AM contamination at the electronic stage. Heterodyne optical receivers, with the local oscillator implemented as a suitable laser, are widely used in the exploration of the earth's atmosphere and in the investigation of astronomical objects. Optical heterodyne detection in the infrared has been associated with the development of lasers. An excellent review of mid-infrared laser heterodyne systems can be found in a recent paper by Parvitte *et al*.[8]

Most optical detectors are ideal heterodyne mixers because their response is proportional to the intensity of illumination, *i.e.* it is quadratic in the electric field. Let two optical waves of identical polarization be incident on such a detector, one coming from the free-space communication link, the other from a local oscillator. The individual waves are represented by the time-dependent fields,

$$\begin{aligned} E_0(t) &= \sqrt{I_0}\cos\left(2\pi f_0 t + \varphi(t)\right), \\ E_{\mathrm{LO}}(t) &= \sqrt{I_{\mathrm{LO}}}\cos\left(2\pi f_{\mathrm{LO}} t\right), \end{aligned} \tag{3}$$

where I_0 and I_{LO} are, respectively, the intensities that would be measured for each of the waves individually. If the two waves are detected simultaneously and if the detector is able to respond to the intermediate frequency $f_{\mathrm{IF}} \equiv f_0 - f_{\mathrm{LO}}$, then the measured intensity will have a time-dependent component,

$$I_{\mathrm{IF}}(t) = \sqrt{I_{\mathrm{LO}} I_0} \cos\left[2\pi\left(f_0 - f_{\mathrm{LO}}\right)t + \varphi(t)\right]. \tag{4}$$

Note that the time-dependent phase information, corresponding to the frequency modulation of the free-space communication signal, is inherited by the beat oscillation, which therefore remains an FM signal. In a single-channel communication system, the intermediate frequency should be in the range accessible to electronic amplifiers (less than ~100 GHz). It should be noted, however, that for practical reasons, the intermediate frequency must be larger than the excursion range of the modulated signal,

$$f_S << \Delta F << f_{\mathrm{IF}}, \tag{5}$$

so that one could use a narrow-band limiting amplifier, rather than a much more cumbersome wideband electronic system. It is well-known that narrow-band amplifiers offer better stability against self-excitation and permit higher gain.

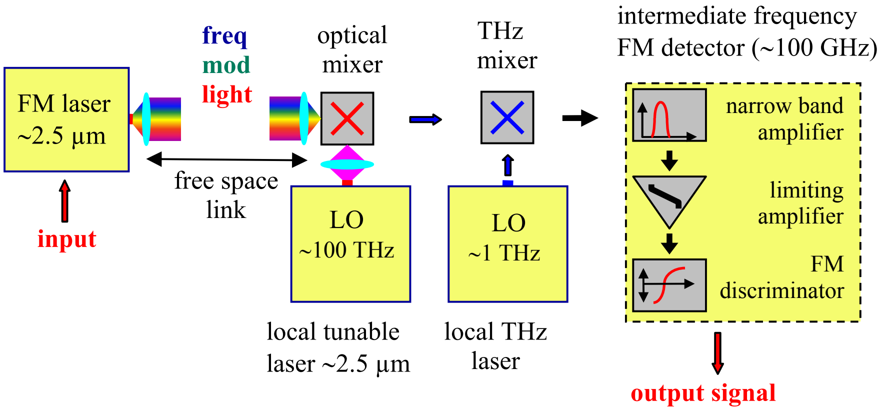

Fig. 5. Schematic diagram of a multi-channel free-space communication link based on optical frequency modulation and heterodyne detection

It is evident from Eq. (4), that heterodyne detection not only downconverts the FM signal to a lower intermediate frequency, but also offers amplification of the weak signal, since the LO power can exceed that received from the free-space link by many orders of magnitude, $I_{LO} >> I_0$. As is well-known in the field of astronomical spectroscopy,[8] the application fields of heterodyne detection are either phase/frequency measurements or measurements of a weak signal. Optical free-space communications can take advantage of both features.

The described heterodyne detection scheme is good for one channel. If more than one channel is desired, as should be the case in many applications, one can use two down-conversions, as illustrated in Fig. 5. The channel spacing is in THz range and the channel is selected by tuning the optical LO. The intermediate THz frequency is then mixed with a second LO (nontunable) thus bringing the intermediate frequency to the "electrical domain". Terahertz quantum cascade lasers[9-11] appear to be ideal candidates for this task.

4. Conclusion

We consider an optical communication system based on optical frequency modulation. Such a system is very attractive in that it allows to deploy the enormous excess bandwidth that exists in the optical frequency range for the goal of relaxing the demands on the transmission power. Optical FM appears feasible, based on tunable diode lasers and heterodyne detection. Development of fast tunable mid-infrared semiconductor lasers is the enabling technology for both its send and receive components.

We considered free-space communication links as the primary application of optical FM and identified accordingly the wavelength ranges around 2.75 μm for terrestrial links and 8 – 10 μm for intersatellite communications. The same principles, however, can be used at other wavelengths, e.g., in the visible in outer space, or even in fiber-optic communications for the formation of multiple wide-band channels without cross-talk.

5. Acknowledgements

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